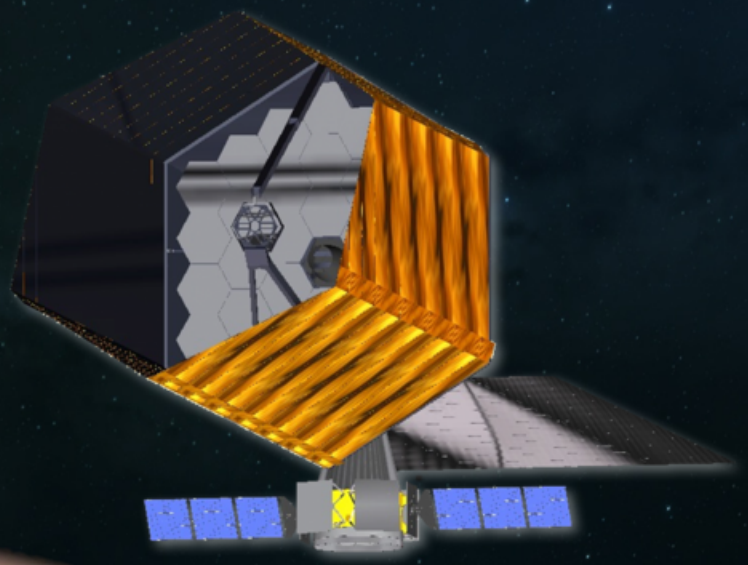
National Aeronautics and Space Administration

NASA

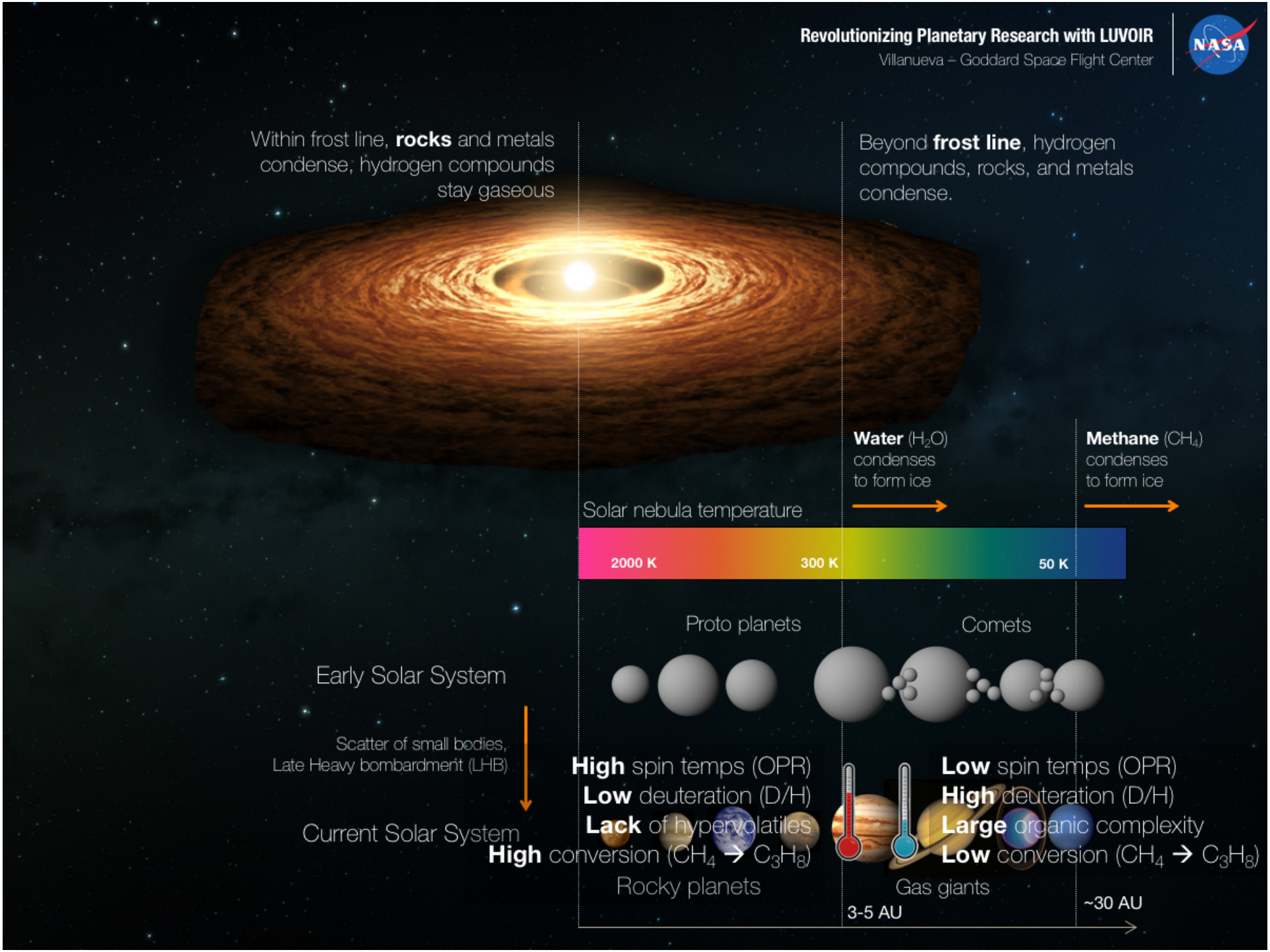
Revolutionizing Planetary Research with **LUVOIR**



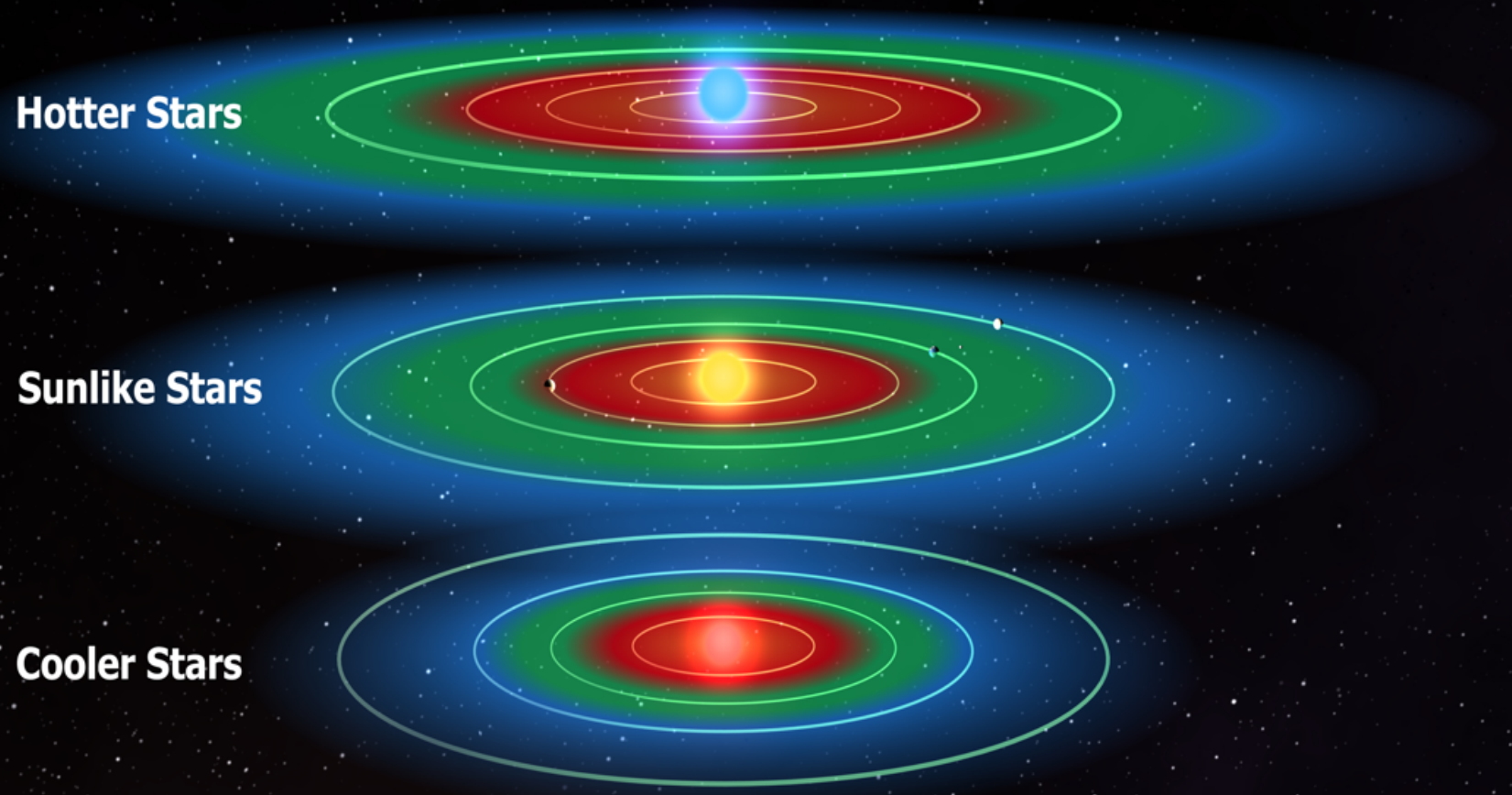
Geronimo Villanueva
(co-chair Solar System WG)

Harris (co-chair), Schmidt (STDT),
Protopapa, Parker, Bodewits,
Rivkin, Bauer, Petro

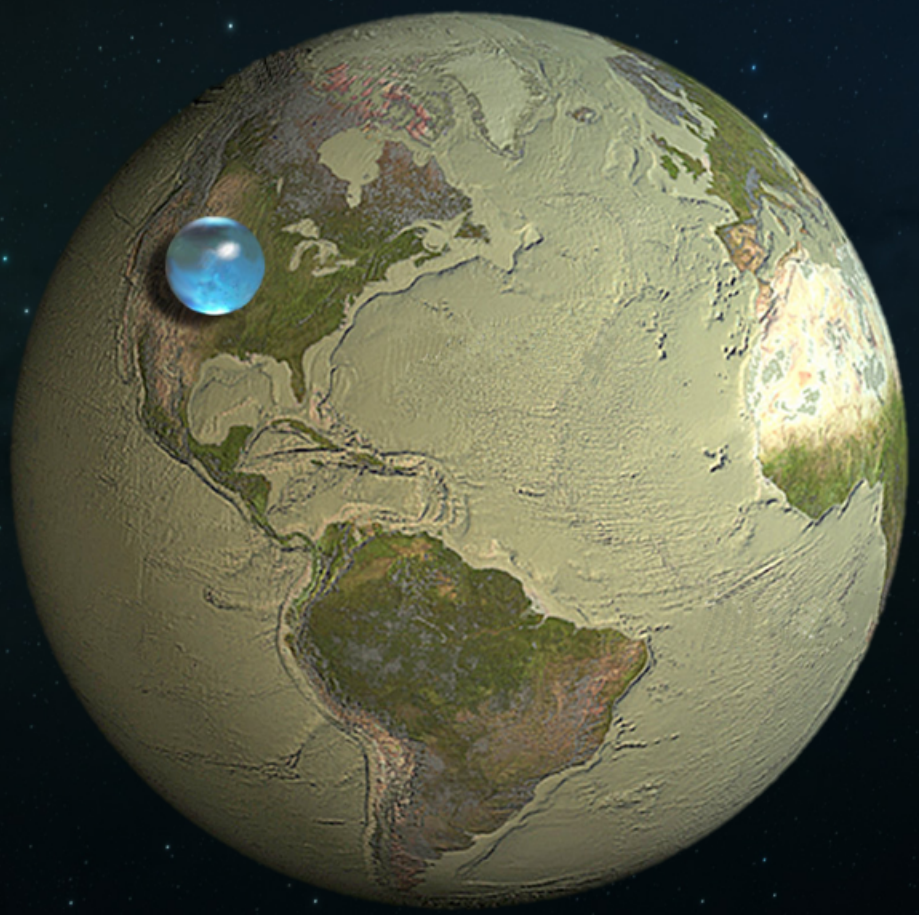
- Probing the **origin** of our Solar System
- Testing for ancient **habitability**
- Searching for **biology** / **geology**
- A bright astronomical future: **LUVOIR** and its siblings


Revolutionizing Planetary Research with LUVOIR
Villanueva – Goddard Space Flight Center
NASA
Within frost line, **rocks** and metals condense; hydrogen compounds stay gaseous
Beyond **frost line**, hydrogen compounds, rocks, and metals condense.
Water (H_2O) condenses to form ice
Methane (CH_4) condenses to form ice
Solar nebula temperature
2000 K
300 K
50 K
Proto planets
Comets
Early Solar System
Scatter of small bodies, Late Heavy bombardment (LHB)
Current Solar System
High spin temps (OPR)
Low deuteration (D/H)
Lack of hypervolatiles
High conversion (CH_4 → C_3H_8)
Rocky planets
Low spin temps (OPR)
High deuteration (D/H)
Large organic complexity
Low conversion (CH_4 → C_3H_8)
Gas giants
3-5 AU
~30 AU

The **water active** region depends on the parent star



Yet, **habitability** requires modest amount of water

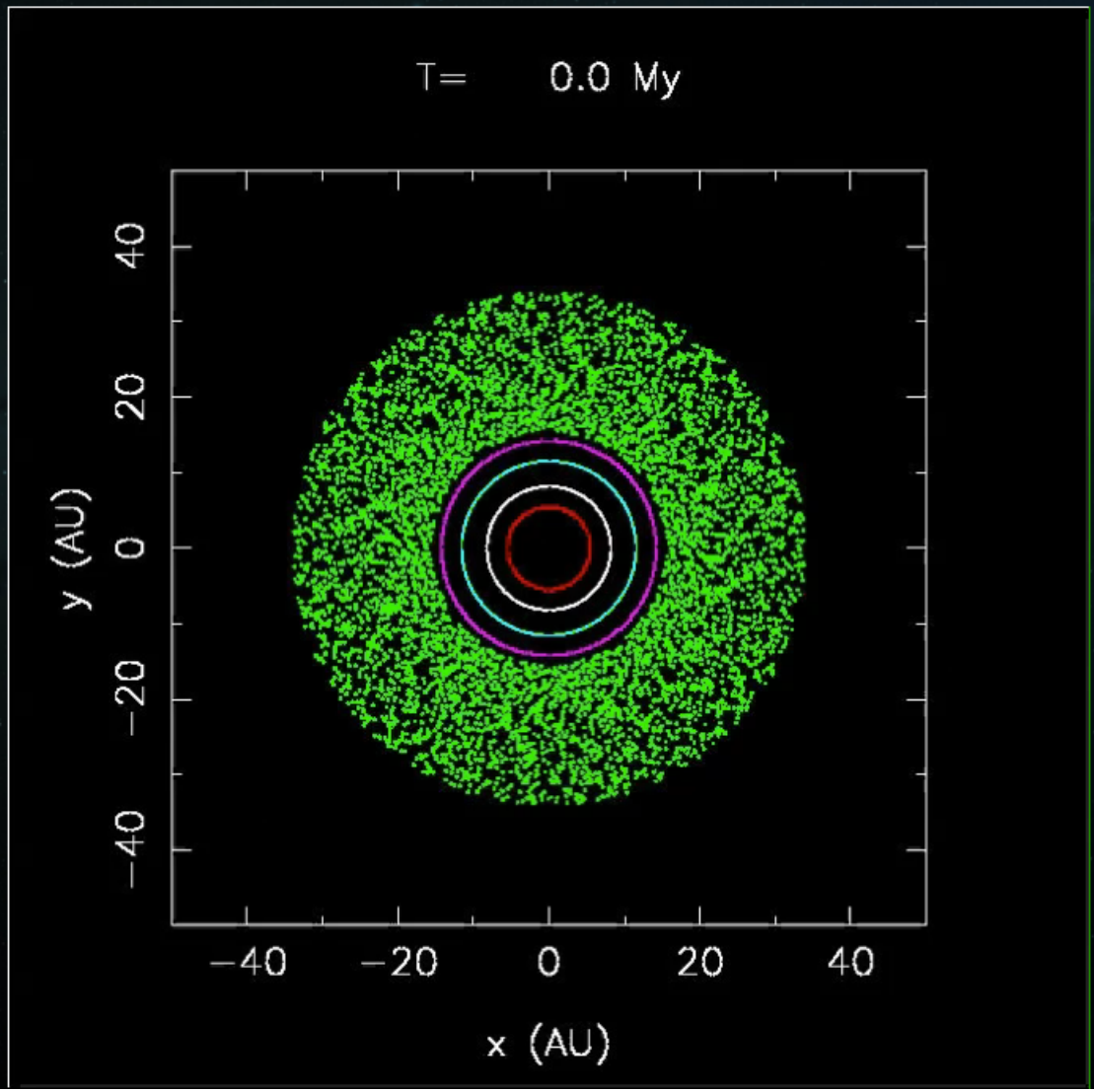


Comparison of the ratio of total volume of water (oceans, rivers, lakes, ice) to total volume of land on Earth (USGS).

And perhaps small icy bodies (e.g. comets) **delivered** this water

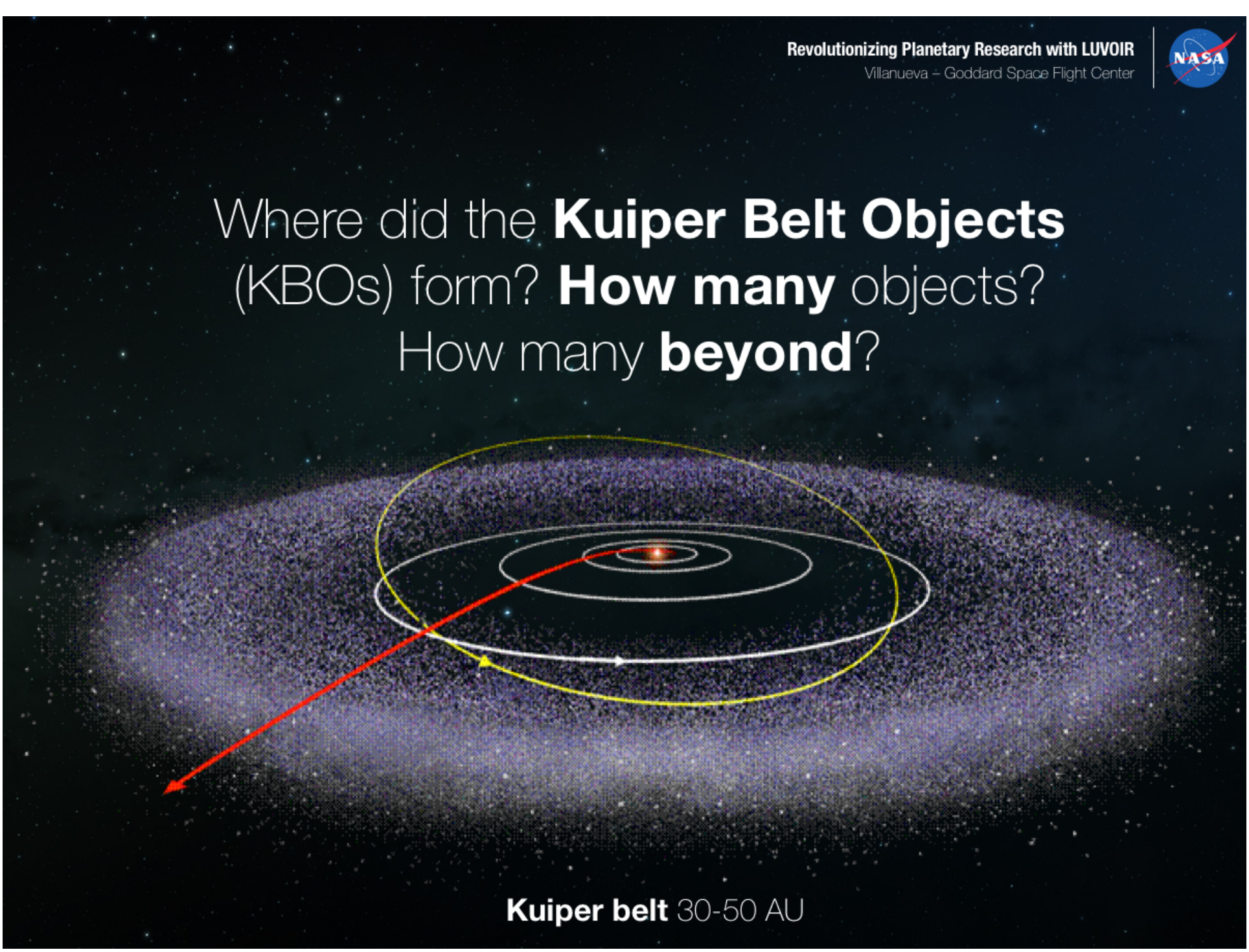
- **Isotopic** ratios (endogenous vs. exogenous)
- **Organic** content (coma vs. nucleus)
- **Ortho / para** ratios (primordial vs. processed)

Comets and Trans-Neptunian-Objects (**TNOs**) also tell us about the formative times



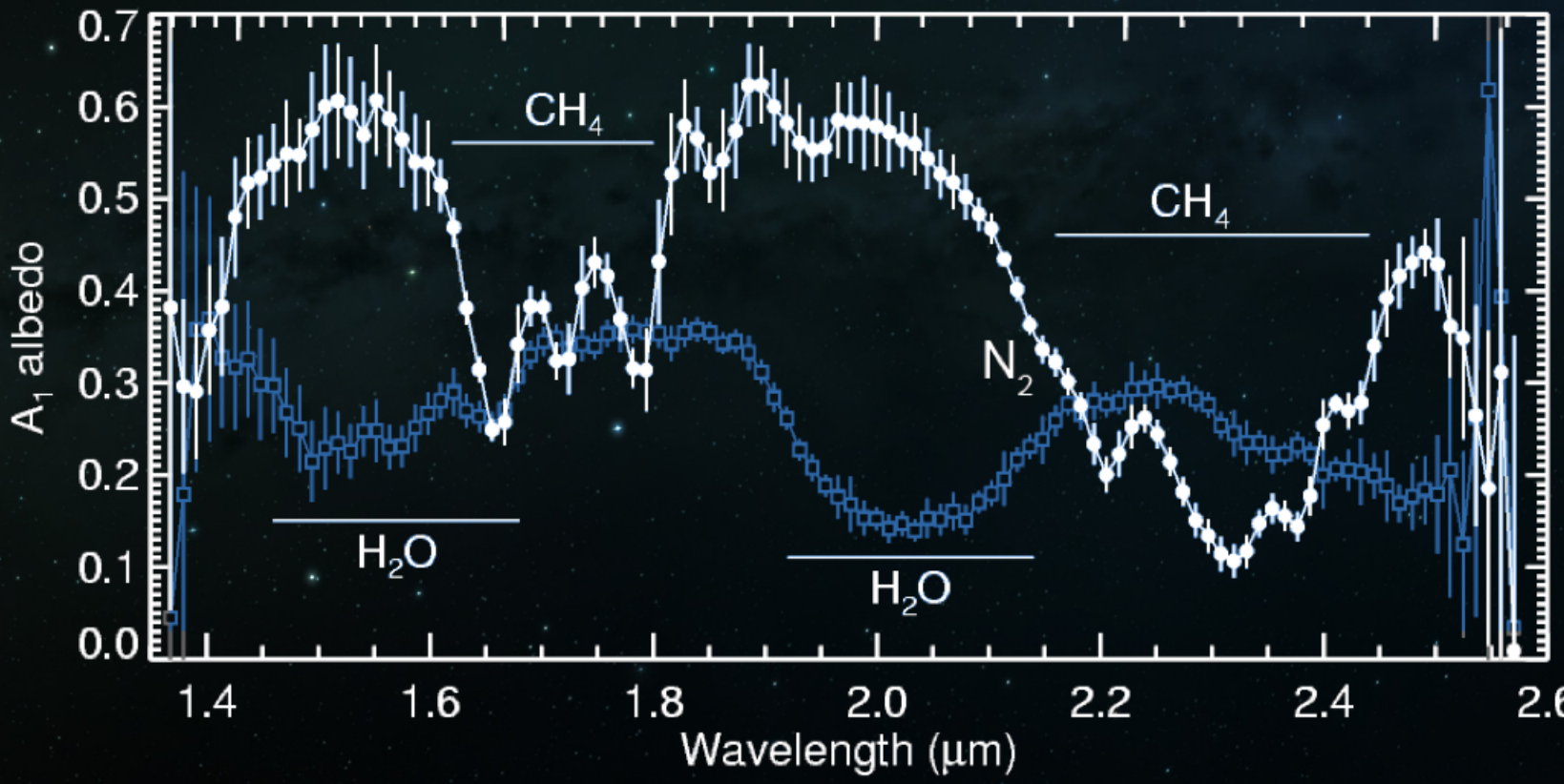
Configuration of the Solar System 4.5 billion years ago, according to the ***Nice model*** (Morbidelli et al. 2005)

Where did the **Kuiper Belt Objects** (KBOs) form? **How many** objects? How many **beyond**?



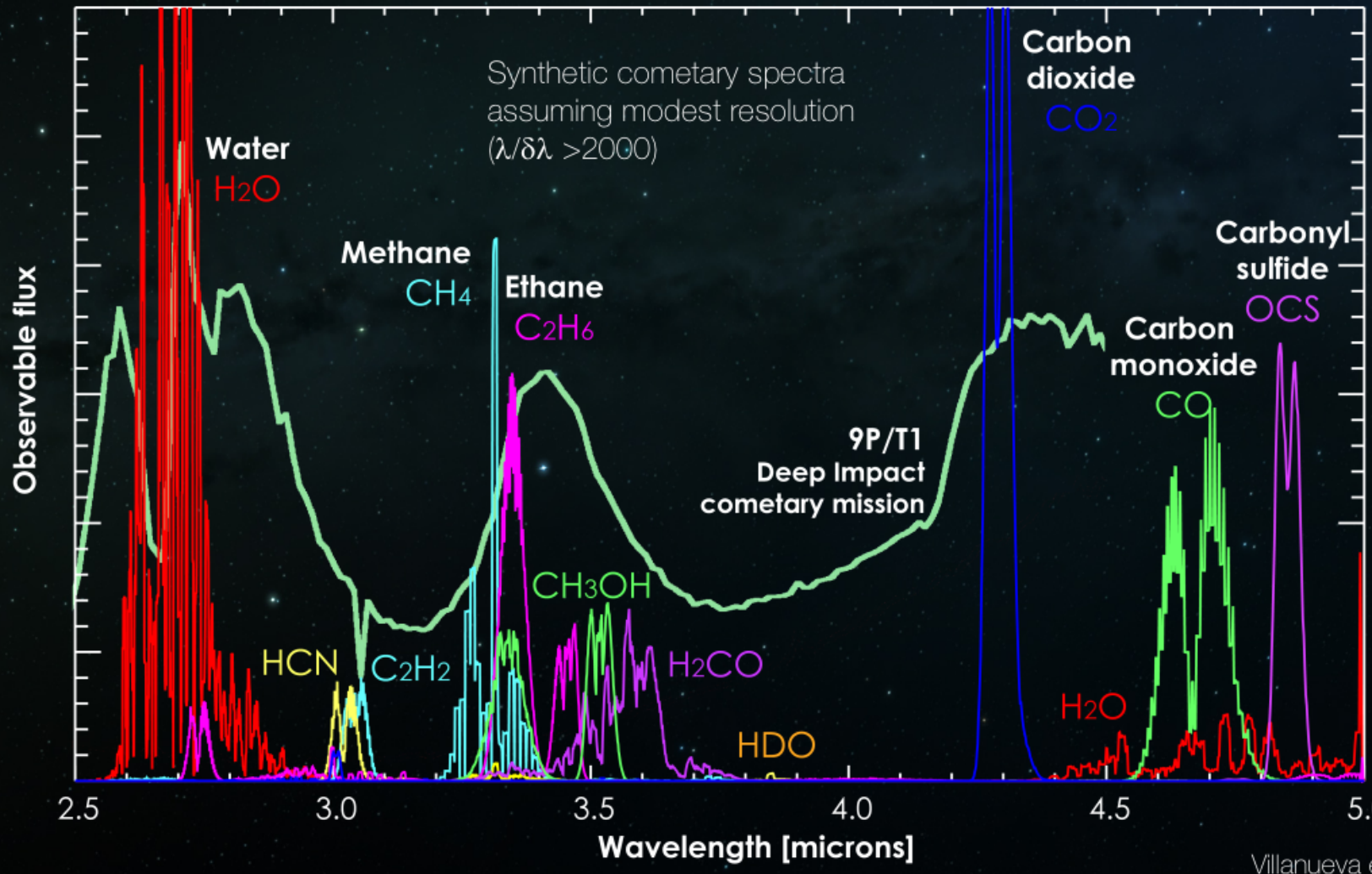
Kuiper belt 30-50 AU

Key **ice signatures** (CH_4, H_2O, N_2) of KBOs are detectable in the 1.3 to 2.6 microns



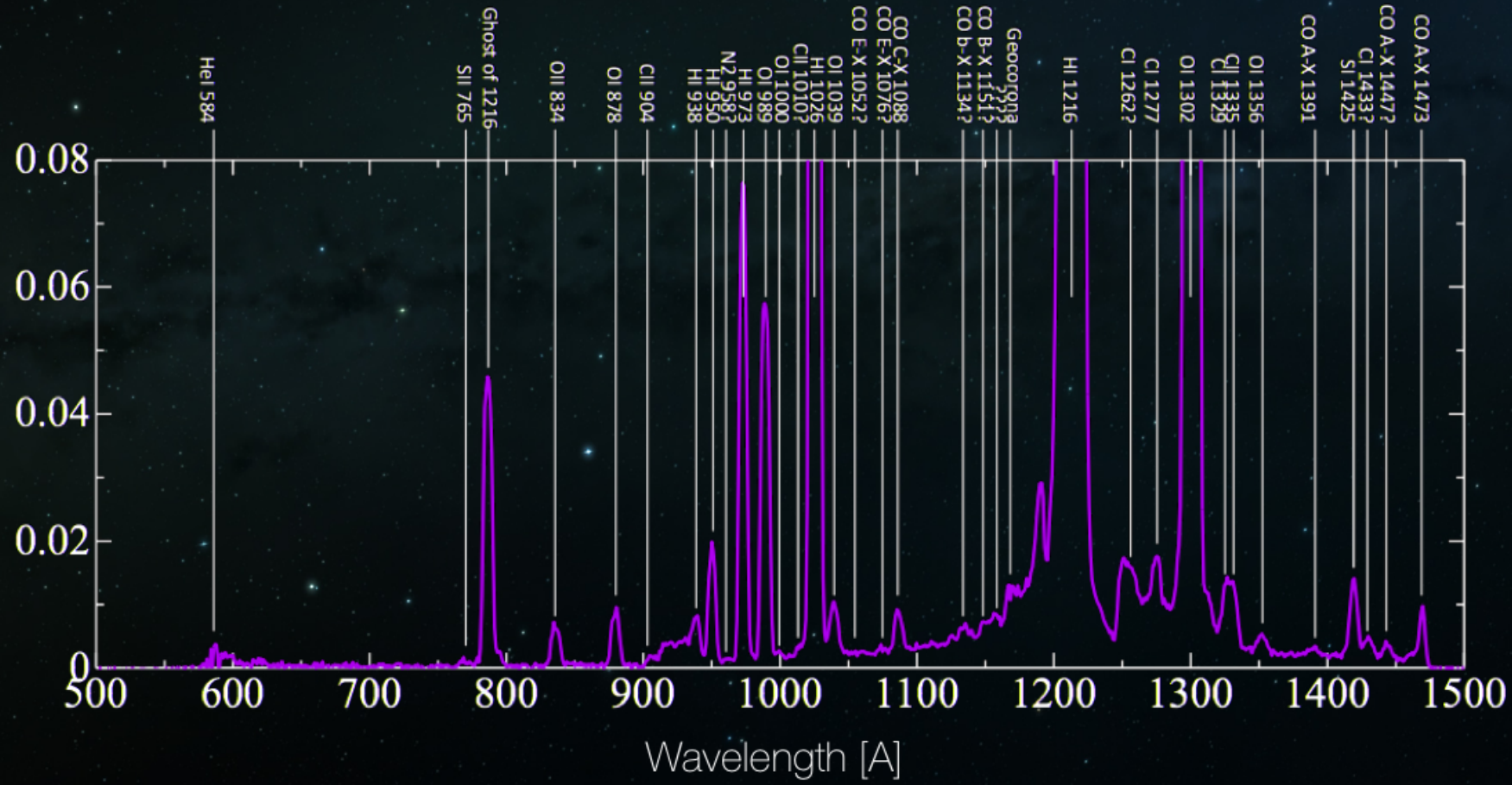
Pluto with HST, Grundy and Buie 2002

And the best way to study **organics** is by measuring the 2.5 to 5 microns region



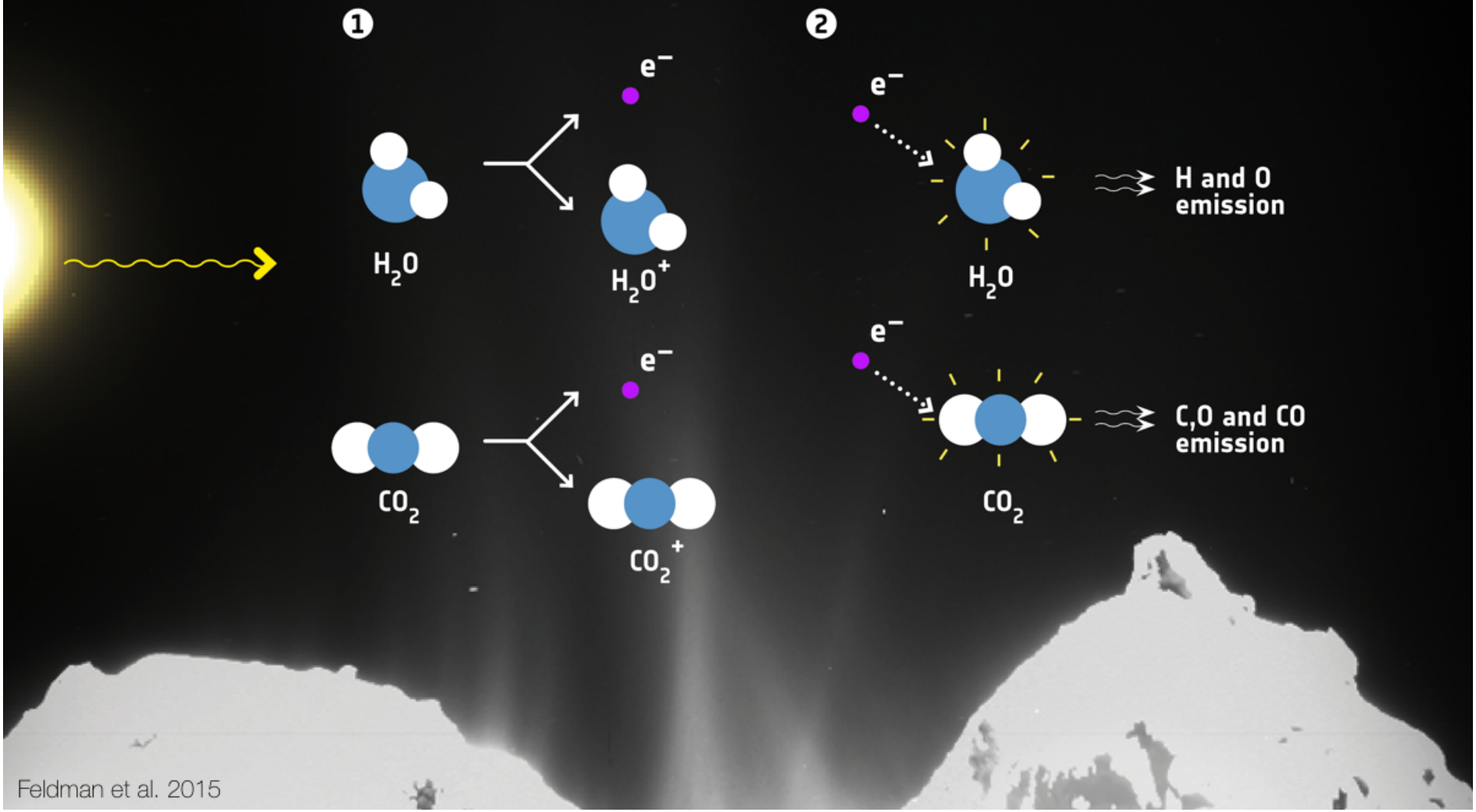
Villanueva et al. 2012

And the **far ultraviolet** reveals the secrets of **high-energy** processes in planetary atmospheres



Comet C/2013 US10 with Hisaki spacecraft, Bodewits, priv. comm.

UV observations with Rosetta of **comet** 67P/CG revealed that **electrons** (not photons) are responsible for the rapid **breakup** of water and carbon molecules erupting from the surface



Feldman et al. 2015

And extreme UV revealed outstanding particle accelerations

Jupiter and Io Plasma Torus

Resonance acceleration of electron by electromagnetic waves.

↓

Forming Jupiter radiation belt.

Region with a strong magnetic field (Jovian inner magnetoshere)

Generated electromagnetic

Region with a weak magnetic field (Jovian outer magnetosphere)

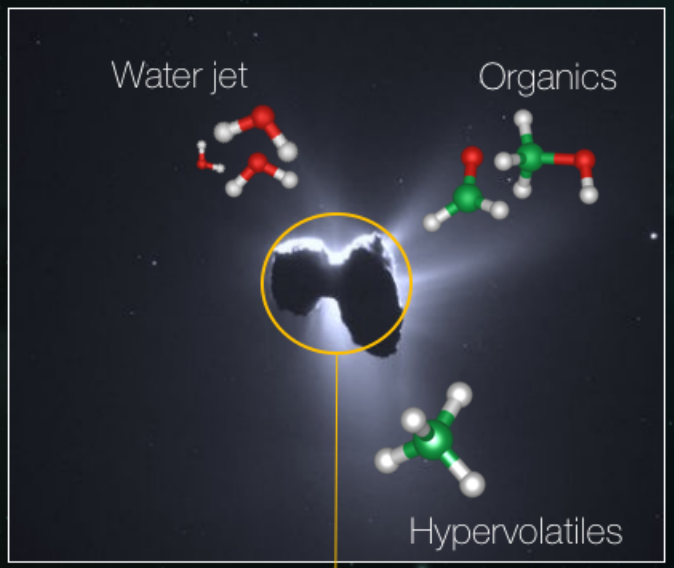
~10keV High-temperatureelectron

The "HISAKI" captured the evidence of high-temperature electron transportation a region with a weak magnetic field to a region with a strong magnetic field.

Yoshioka et al. 2014

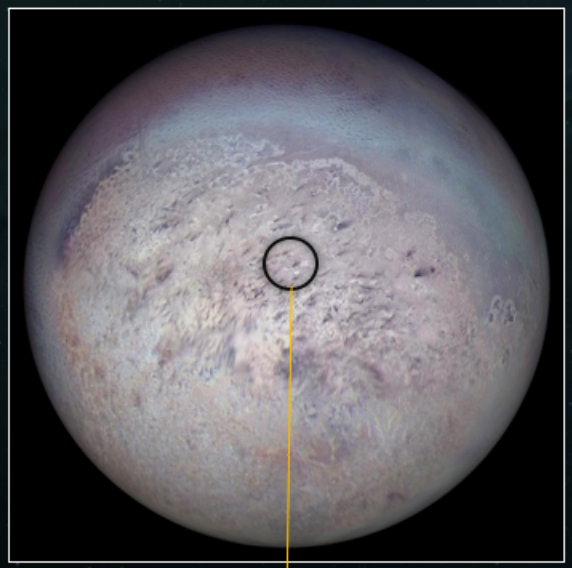
A large space telescope will permit unprecedented spatial resolutions

Resolving **nucleus** / **coma**
Primordial vs. processed?



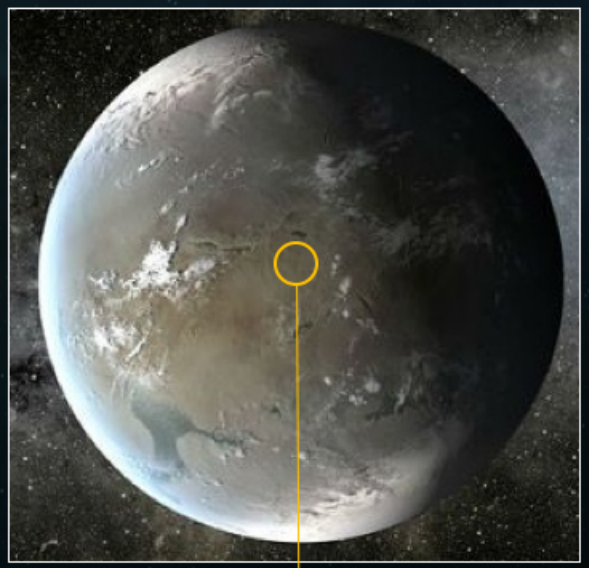
Resolution: **9 km** at 1AU
Telescope: **10 m**
Nucleus of 10 km

Map cryoactivity in **Triton**
and in **most icy moons**



Resolution: **270 km** at 30AU
Telescope: **10 m**
Moon of 2,700 km

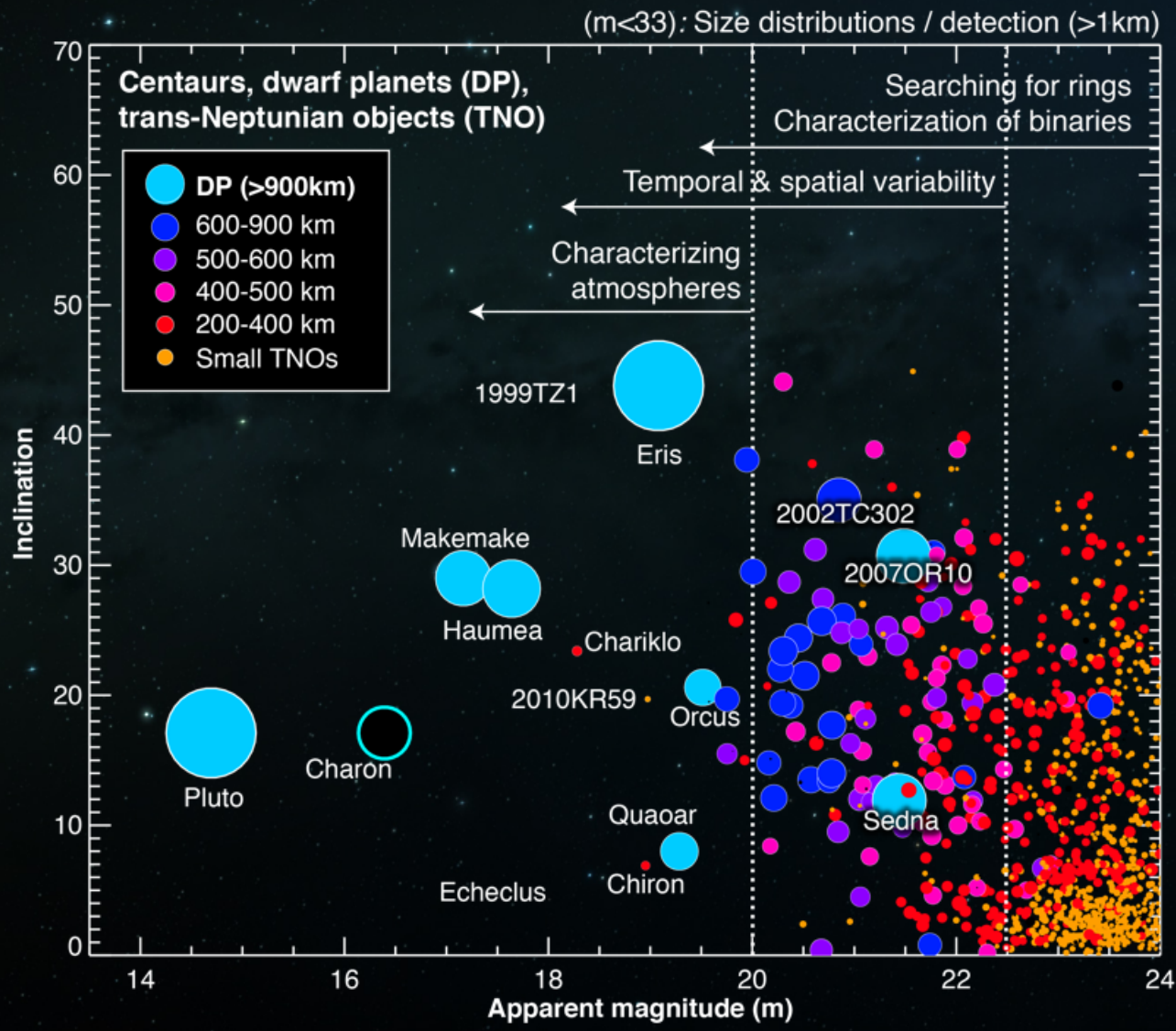
Map the surface of **Planet Nine**
and of many distant KBOs



Resolution: **1800 km** at 200AU
Telescope: **10 m**
Planet of 26,000 km at 200 AU

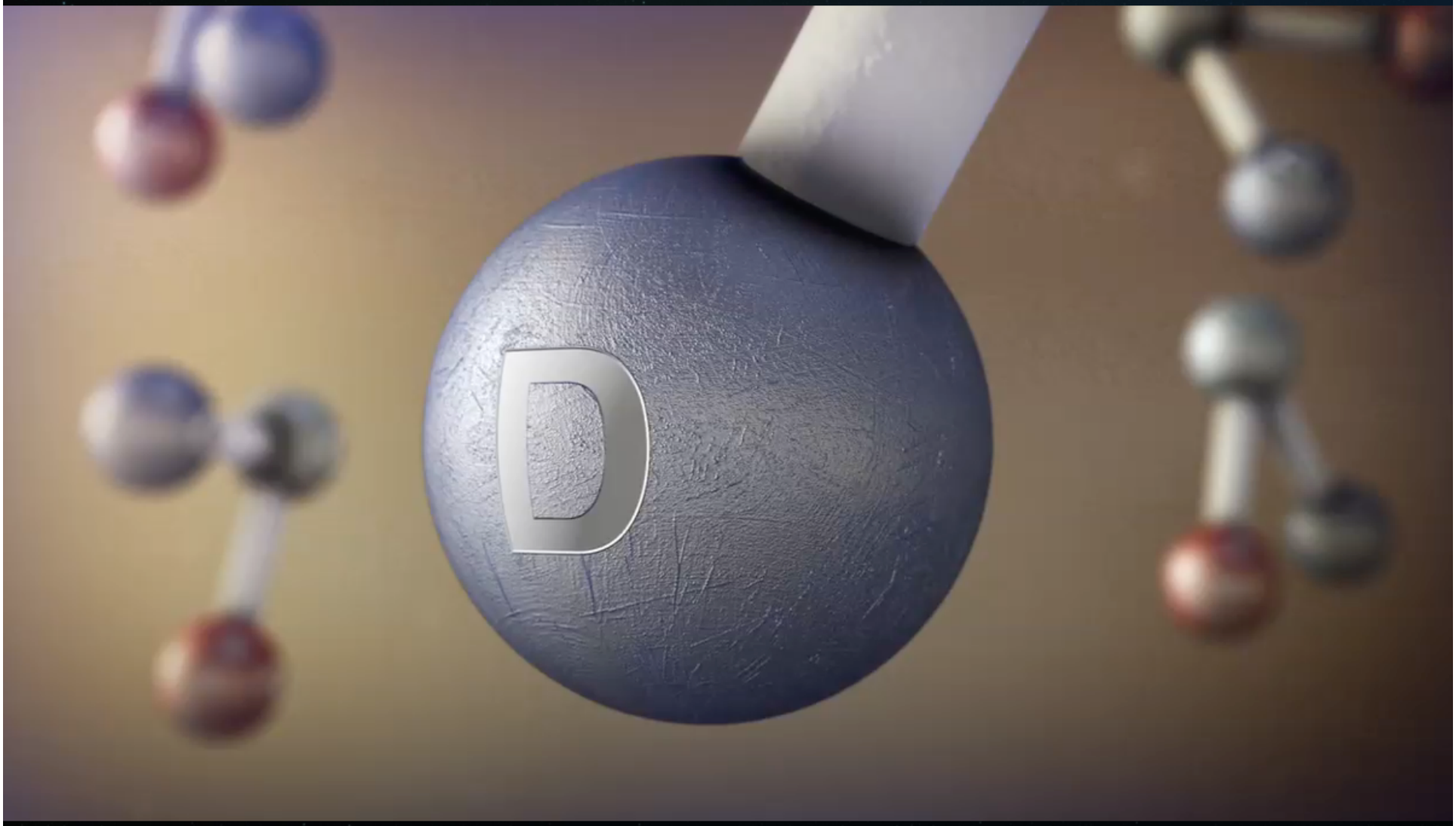
Diffraction limited at optical wavelengths (~13 mas)

Deep characterization of the **outer Solar System** with a 10m space telescope



- Probing the **origin** of our Solar System
  - **Comets** / **asteroids** / **KBO**s (non-sidereal 60 mas/s)
  - **Organic** inventory and **isotopic** ratios
  - Access up to **3.5 microns** (CH-stretch) and **EUV**
  - **Wide field of view** (>8 arcmin) and **IFU** spectroscopy
- Testing for ancient **habitability**
- Searching for **biology** / **geology**

Ancient habitability leaves isotopic signatures …



Villanueva et al., *Science* 2015 and SVS

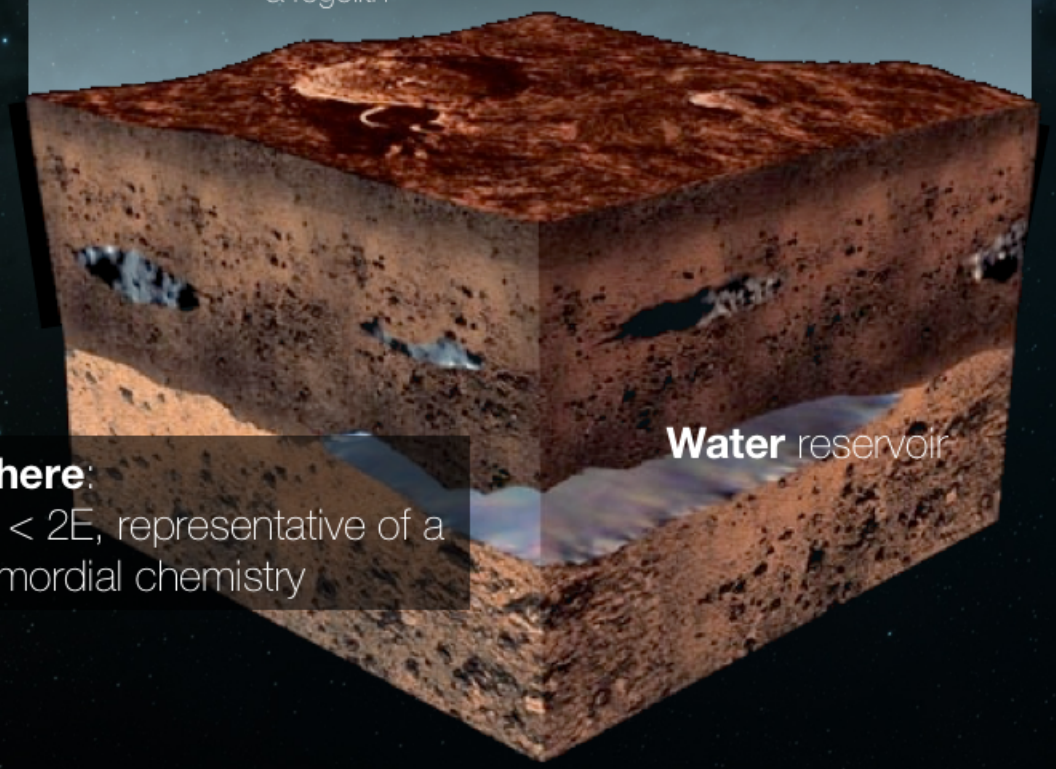
Heavily **enriched**
$(D/H)_{H2O}$

Thermal escape
of lighter isotope

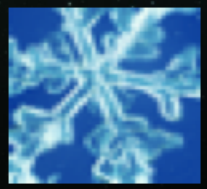
HDO H_2O

Sublimation
condensation

Surface water ice
& regolith



Water reservoir



Cryosphere:
$(D/H)_{H2O}$ < 2E, representative of a more primordial chemistry

E: Terrestrial value (VSMOW)

Heavily **enriched**
$(D/H)_{H2O}$

Low primordial
$(D/H)_{H2O}$

Thermal escape
of lighter isotope

HDO H_2O

Sublimation
condensation

Surface water ice
& regolith

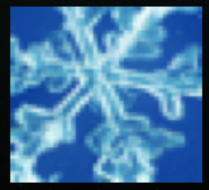
HDO H_2O

Release from
sub-surface reservoir?

Vent

Water reservoir

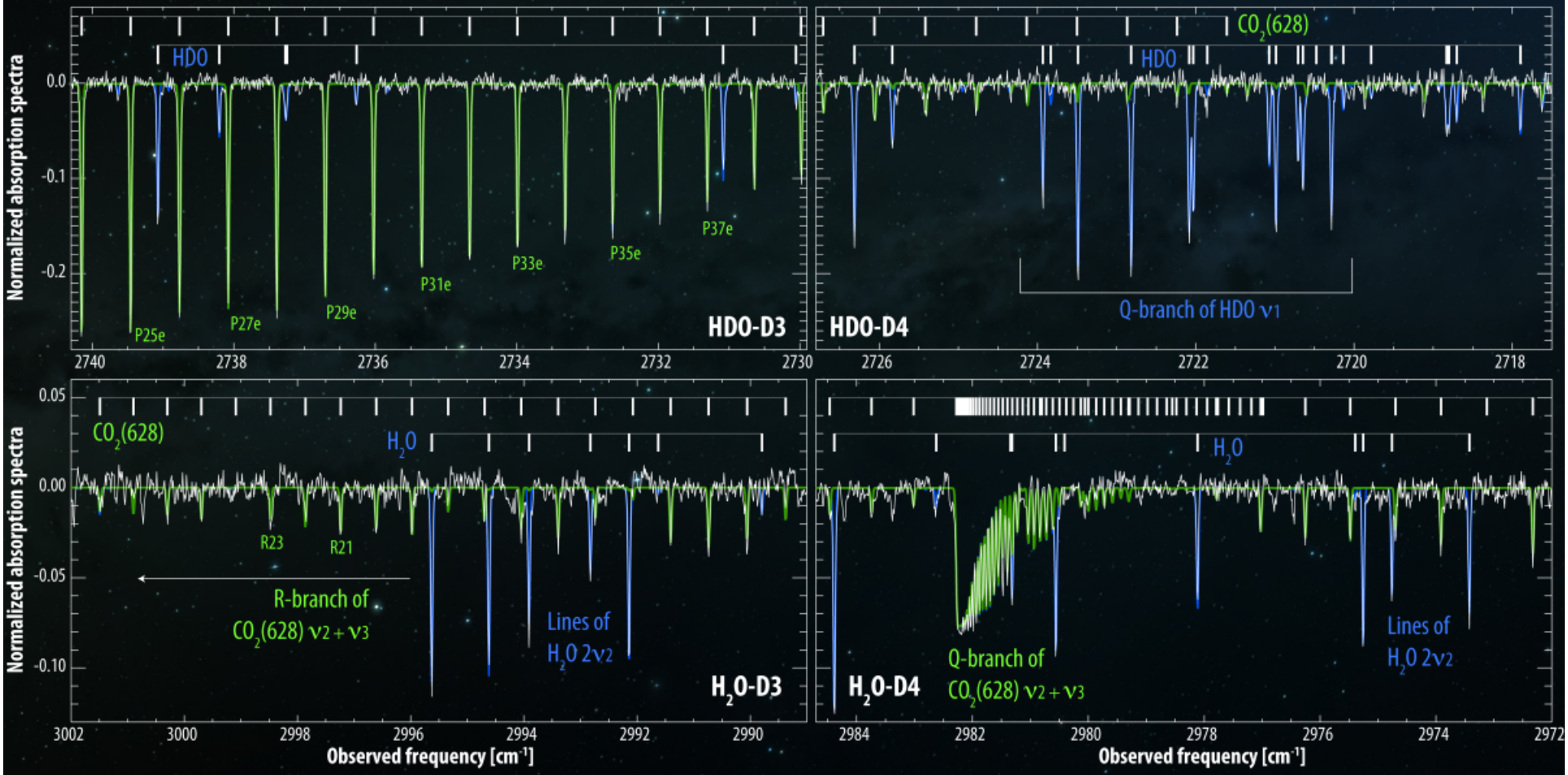
The $(D/H)_{H2O}$ ratio reveals **the loss of water** from Mars and the age of the sensed gas.



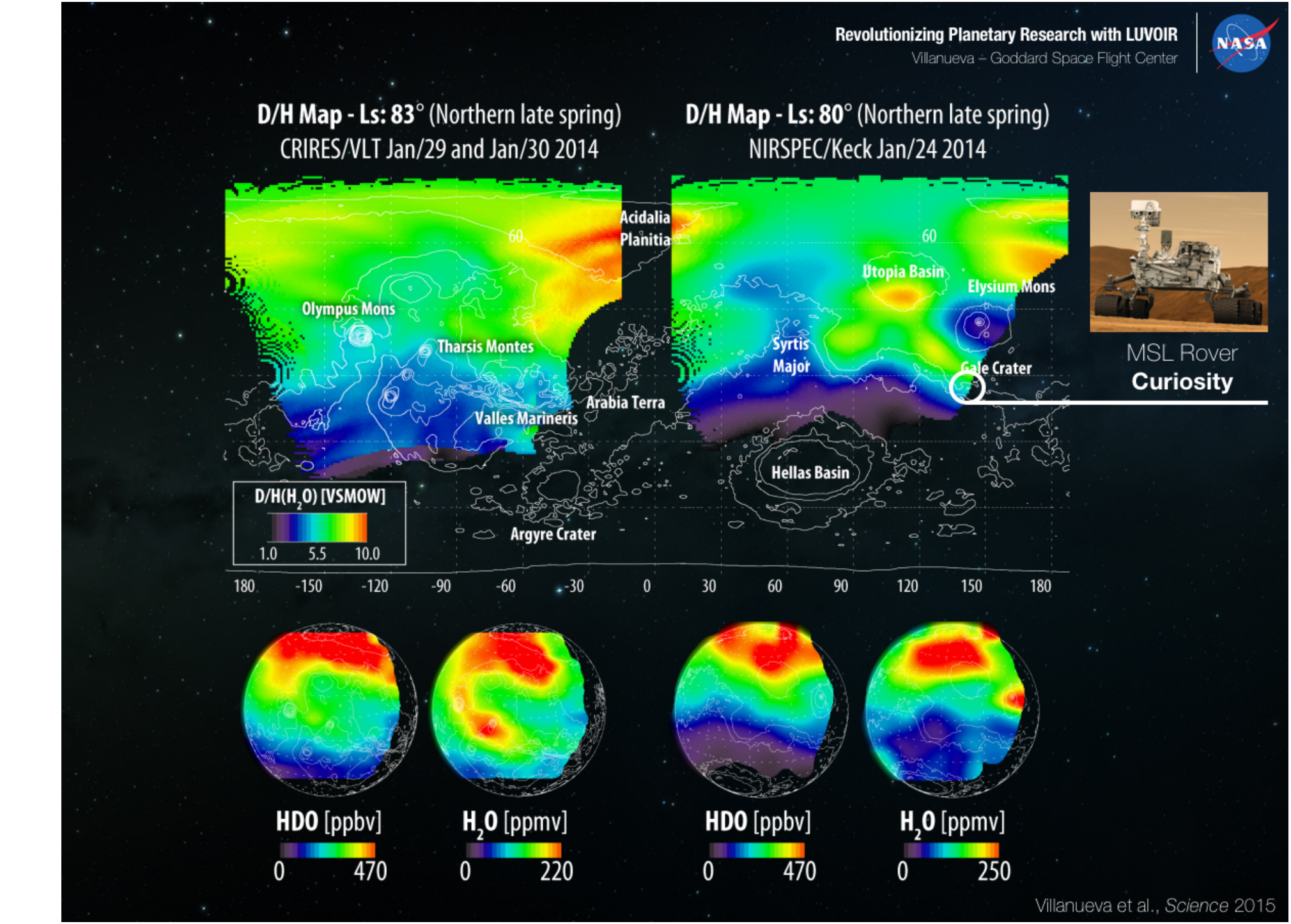
Cryosphere:
$(D/H)_{H2O}$ < 2E, representative of a more primordial chemistry

E: Terrestrial value (VSMOW)

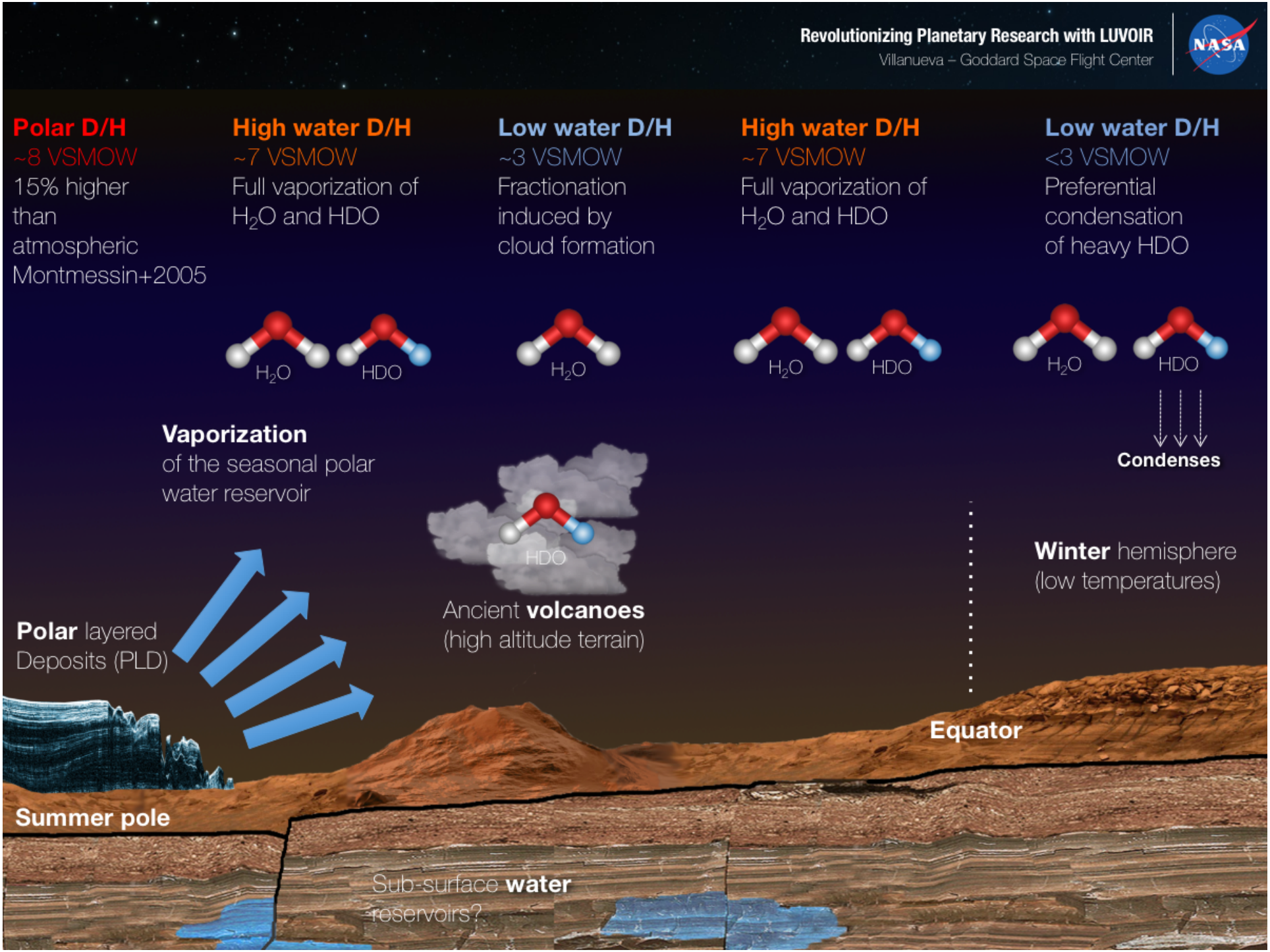
Mapping water D/H requires **high resolving power** ($\lambda/\delta\lambda$ > 50,000)



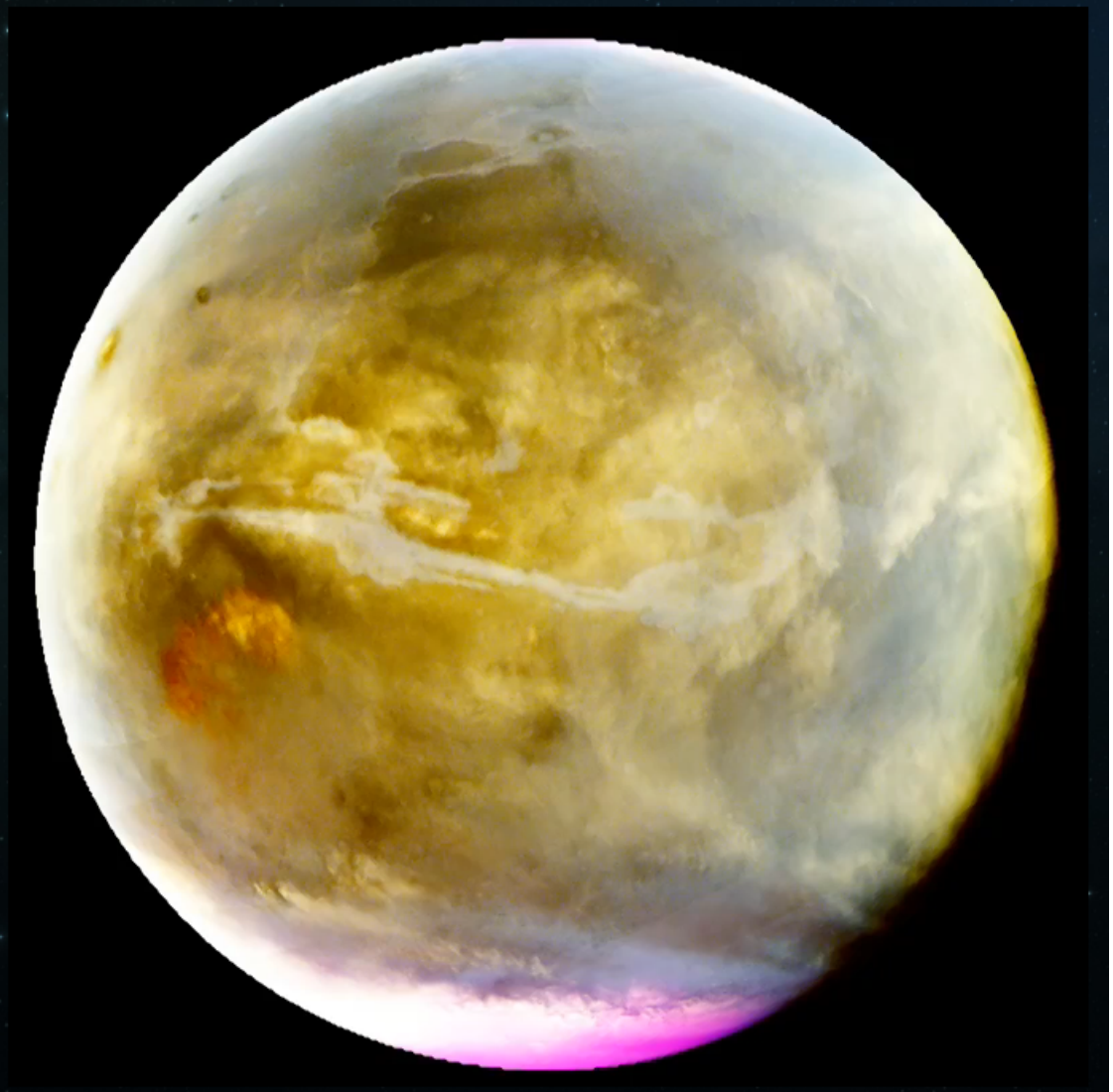
CRIRES/VLT, Villanueva et al., *Science* 2015



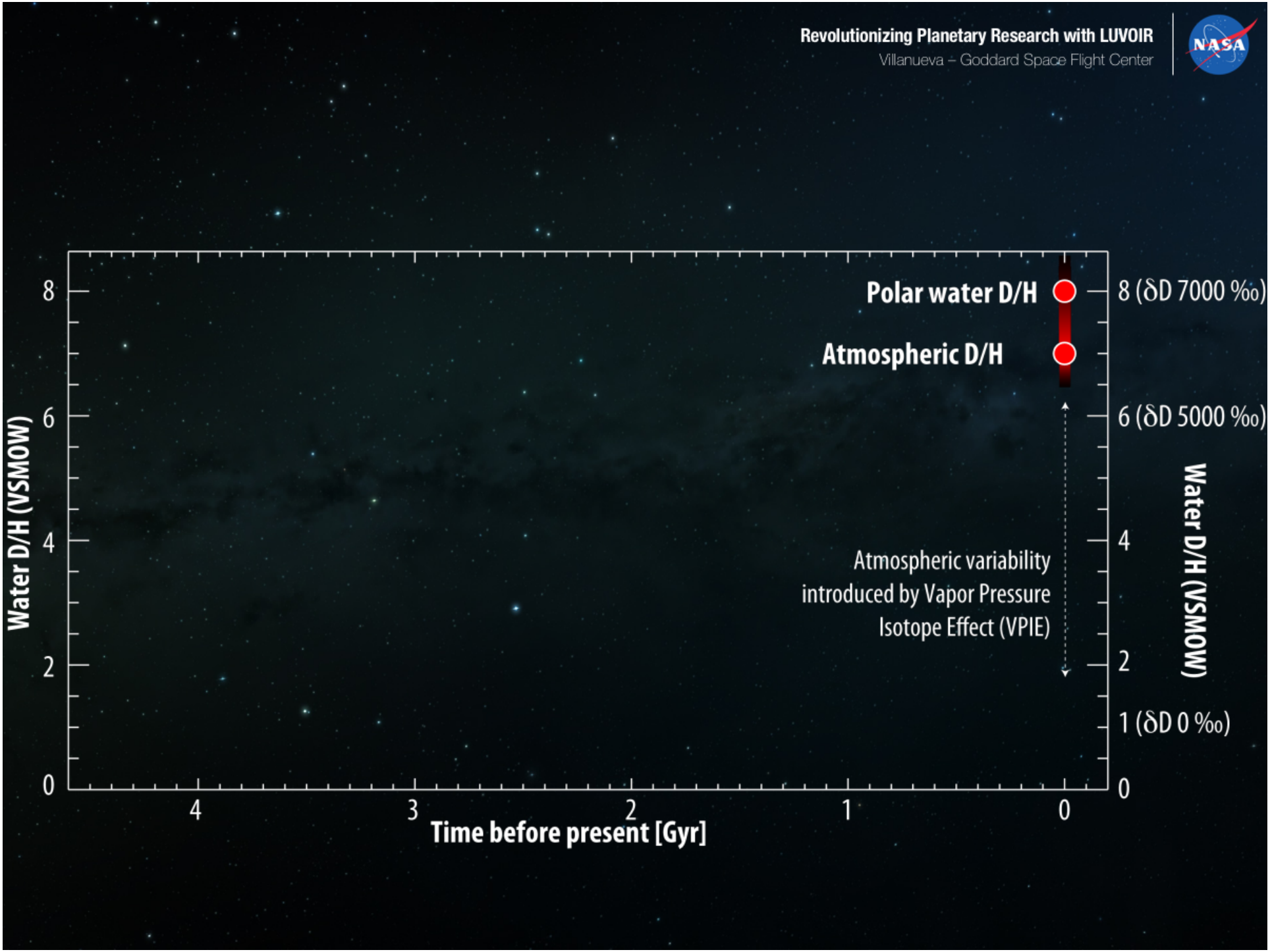
Villanueva et al., *Science* 2015

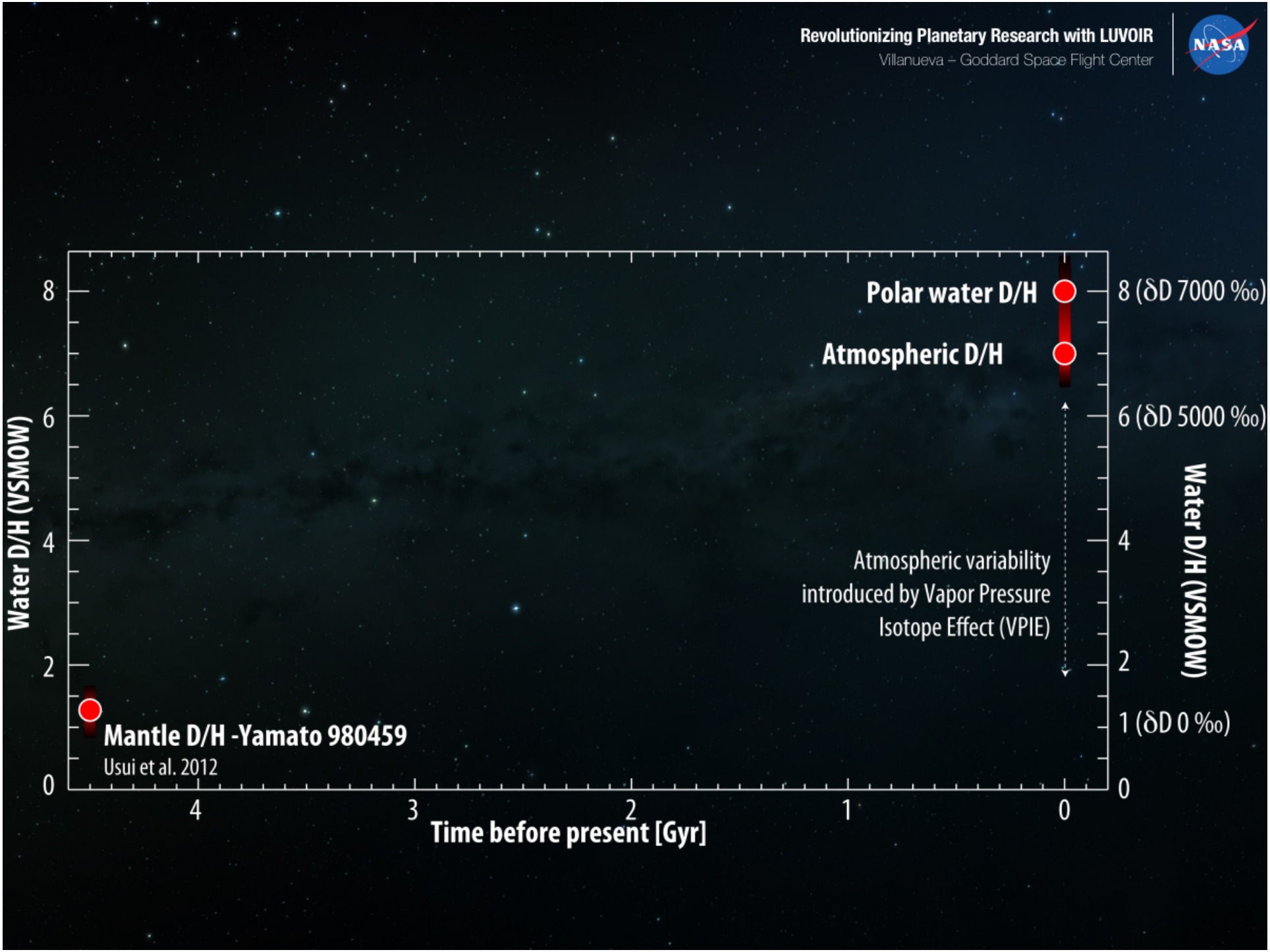

Polar D/H
~8 VSMOW
15% higher than atmospheric Montmessin+2005
High water D/H
~7 VSMOW
Full vaporization of H_2O and HDO
Low water D/H
~3 VSMOW
Fractionation induced by cloud formation
High water D/H
~7 VSMOW
Full vaporization of H_2O and HDO
Low water D/H
<3 VSMOW
Preferential condensation of heavy HDO
H_2O
HDO
H_2O
H_2O
HDO
H_2O
HDO
Condenses
Vaporization of the seasonal polar water reservoir
HDO
Ancient volcanoes (high altitude terrain)
Winter hemisphere (low temperatures)
Polar layered Deposits (PLD)
Equator
Summer pole
Sub-surface water reservoirs?

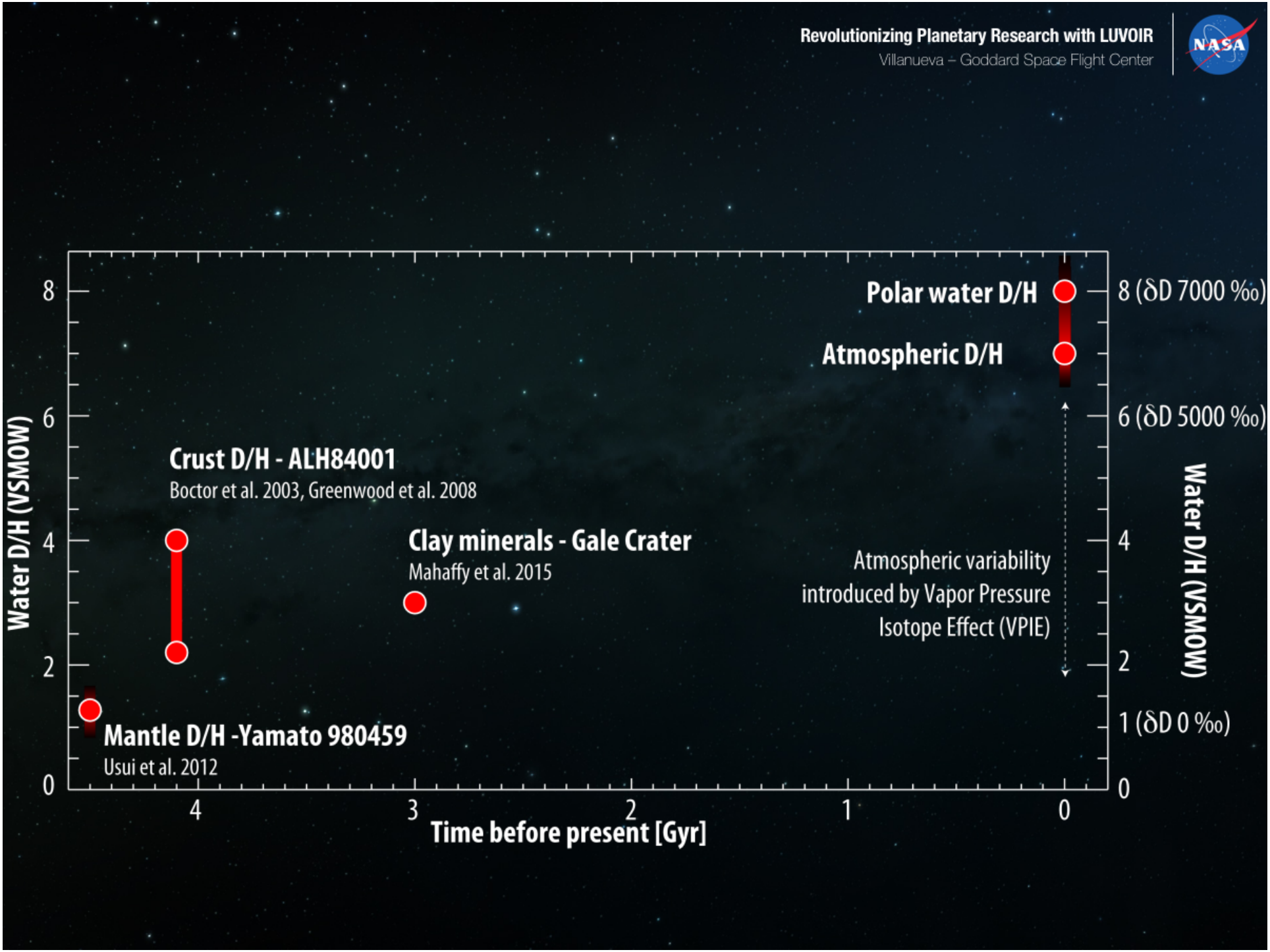
And, **UV mapping** allows us to see these processes in action, and to observe atmospheric escape



Clouds and aerosols appear as a white "hazy" color, while intense dayglow is observed in the southern pole (MAVEN)


Polar water D/H
Atmospheric D/H
Atmospheric variability
introduced by Vapor Pressure
Isotope Effect (VPIE)
Water D/H (VSMOW)
0
2
4
6
8
Time before present [Gyr]
4
3
2
1
0
Water D/H (VSMOW)
0
1 (δD 0 ‰)
2
4
6 (δD 5000 ‰)
8 (δD 7000 ‰)


Polar water D/H
Atmospheric D/H
Atmospheric variability
introduced by Vapor Pressure
Isotope Effect (VPIE)
Mantle D/H -Yamato 980459
Usui et al. 2012
Water D/H (VSMOW)
Time before present [Gyr]
8 (δD 7000 ‰)
6 (δD 5000 ‰)
1 (δD 0 ‰)
0
2
4
6
8
3
1


Polar water D/H
Atmospheric D/H
Crust D/H - ALH84001
Boctor et al. 2003, Greenwood et al. 2008
Clay minerals - Gale Crater
Mahaffy et al. 2015
Atmospheric variability introduced by Vapor Pressure Isotope Effect (VPIE)
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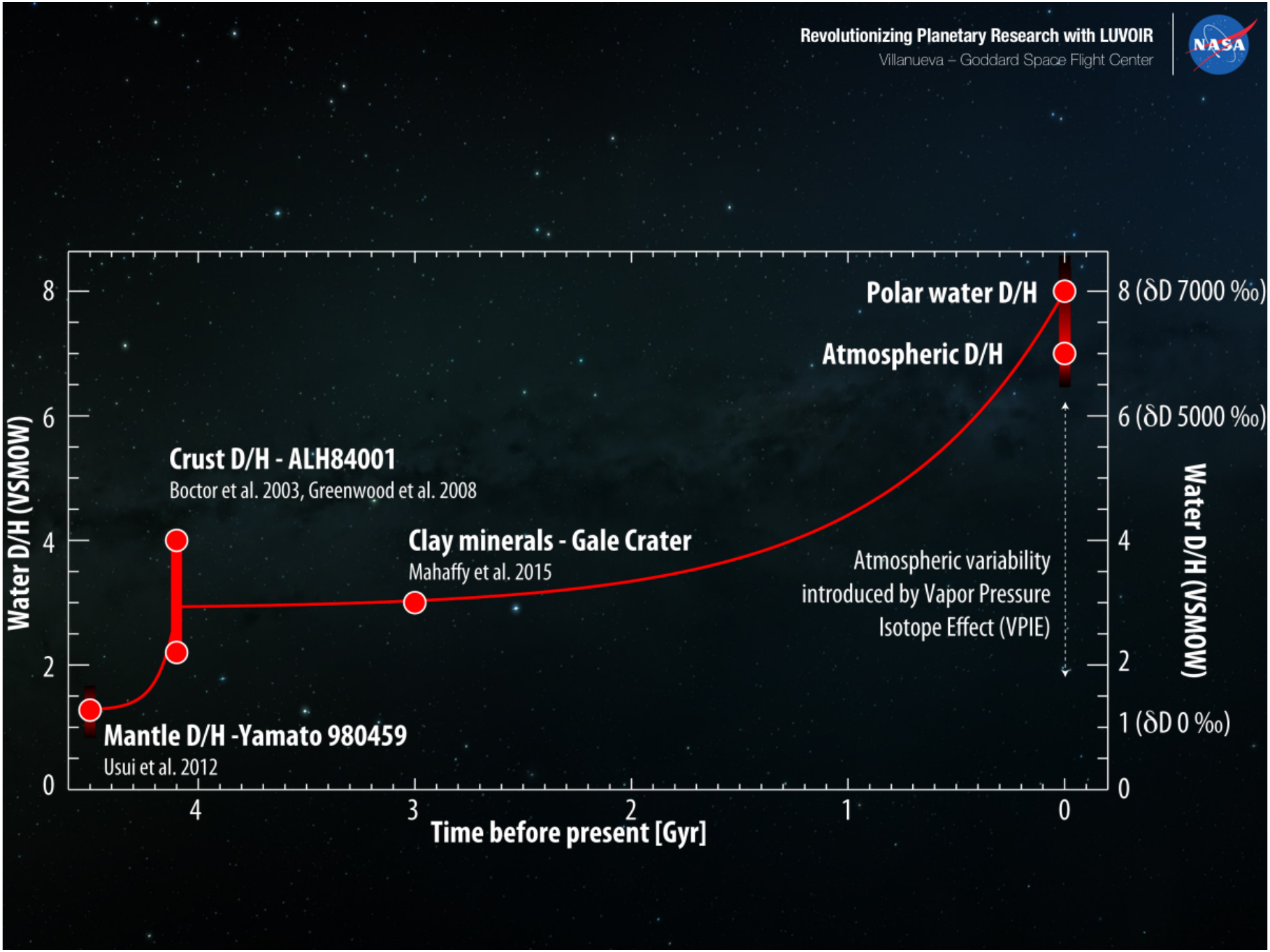
Water D/H (VSMOW)
0
2
4
6
8
Time before present [Gyr]
4
3
2
1
0
Water D/H (VSMOW)
0
1 (δD 0 ‰)
2
4
6 (δD 5000 ‰)
8 (δD 7000 ‰)


Polar water D/H
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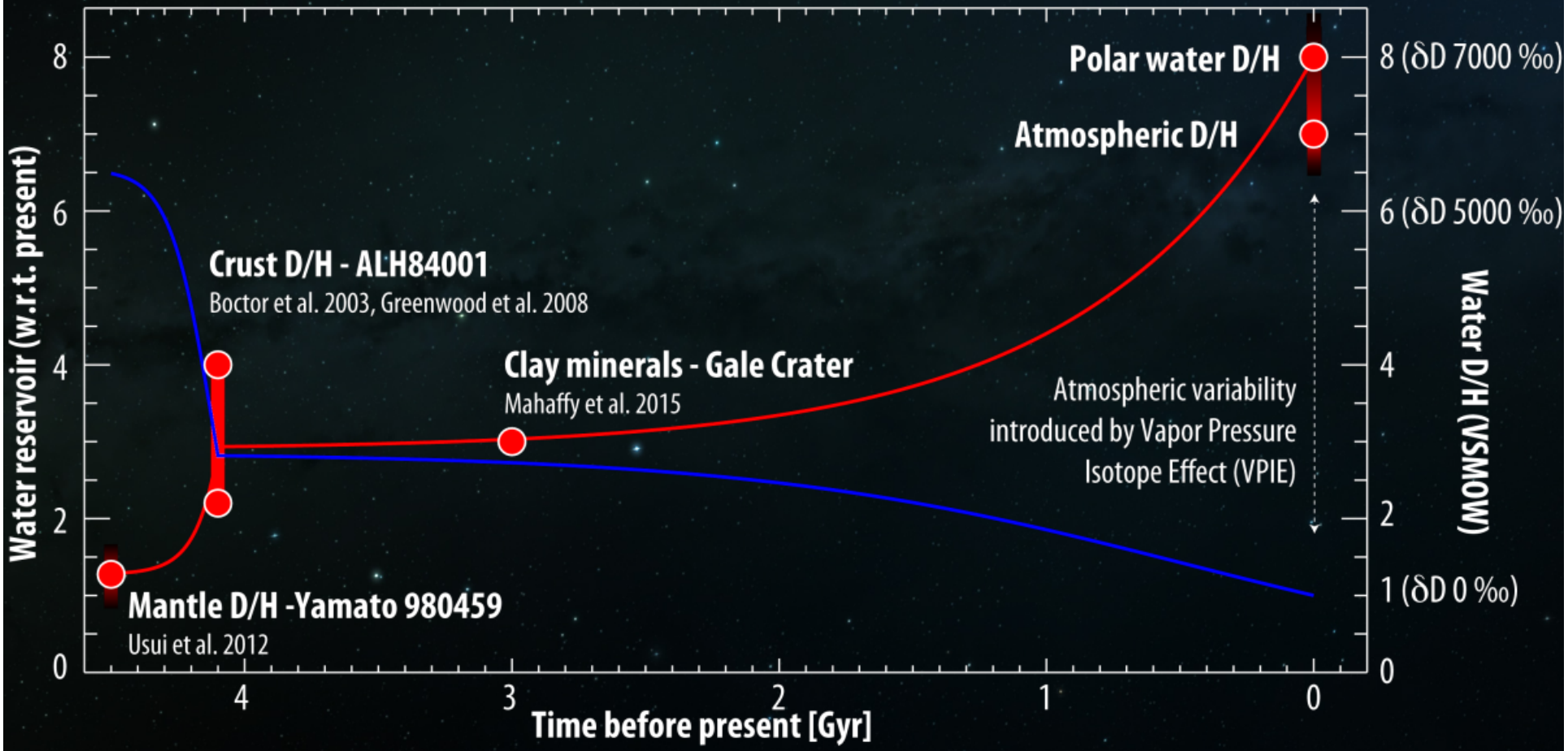
Water D/H (VSMOW)
8 (δD 7000 ‰)
6 (δD 5000 ‰)
4
2
1 (δD 0 ‰)
0
Water D/H (VSMOW)
8
6
4
2
0
4
3
2
1
0
Time before present [Gyr]

Mars had 6.5 times the water that it has today (i.e., **lost 87%** of its water)



Villanueva et al., *Science* 2015

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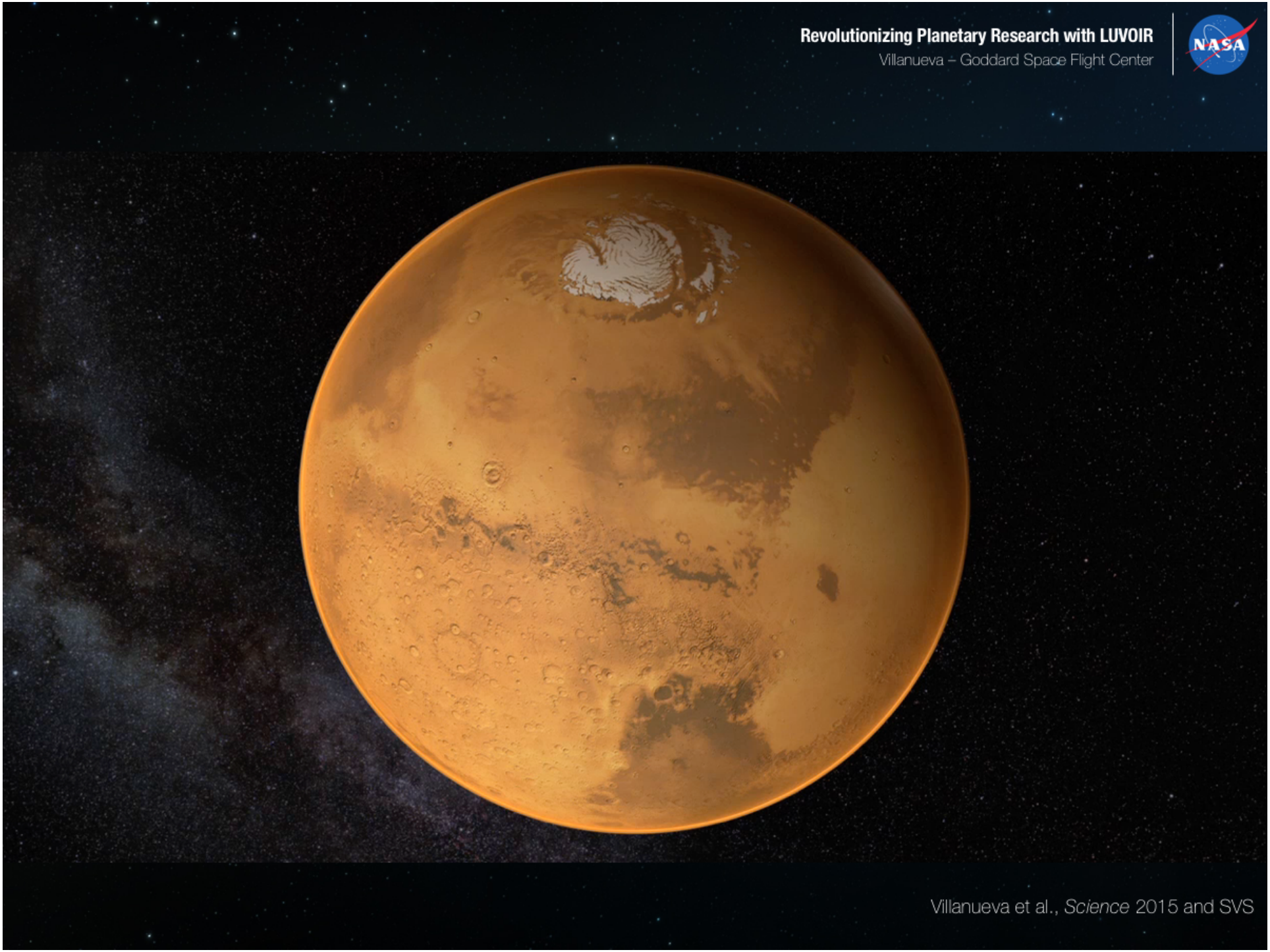
Villanueva – Goddard Space Flight Center



Villanueva et al., *Science* 2015 and SVS

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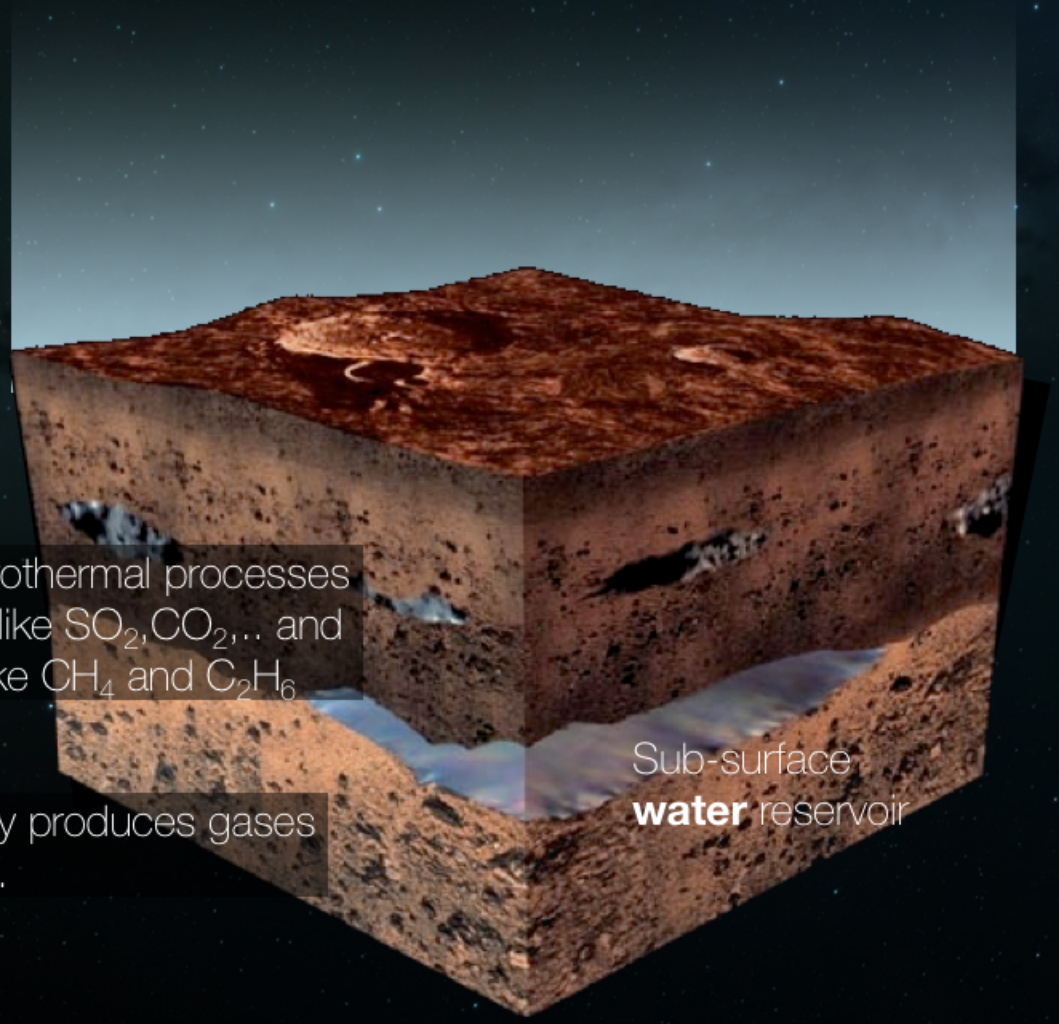
  - **Comets** / **asteroids** / **KBO**s (non-sidereal 60 mas/s)
  - **Organic** inventory and **isotopic** ratios
  - Access to **3.5 microns** (CH-stretch) and **EUV**
  - **Wide field of view** (>8 arcmin) and **IFU** spectroscopy
- Testing for ancient **habitability**
  - Access to **3.7 microns** (HDO fundamental) and **UV**
  - High flux **dynamic range** (weak and bright sources)
  - **High resolving power** (>50,000)
- Searching for **biology** / **geology**

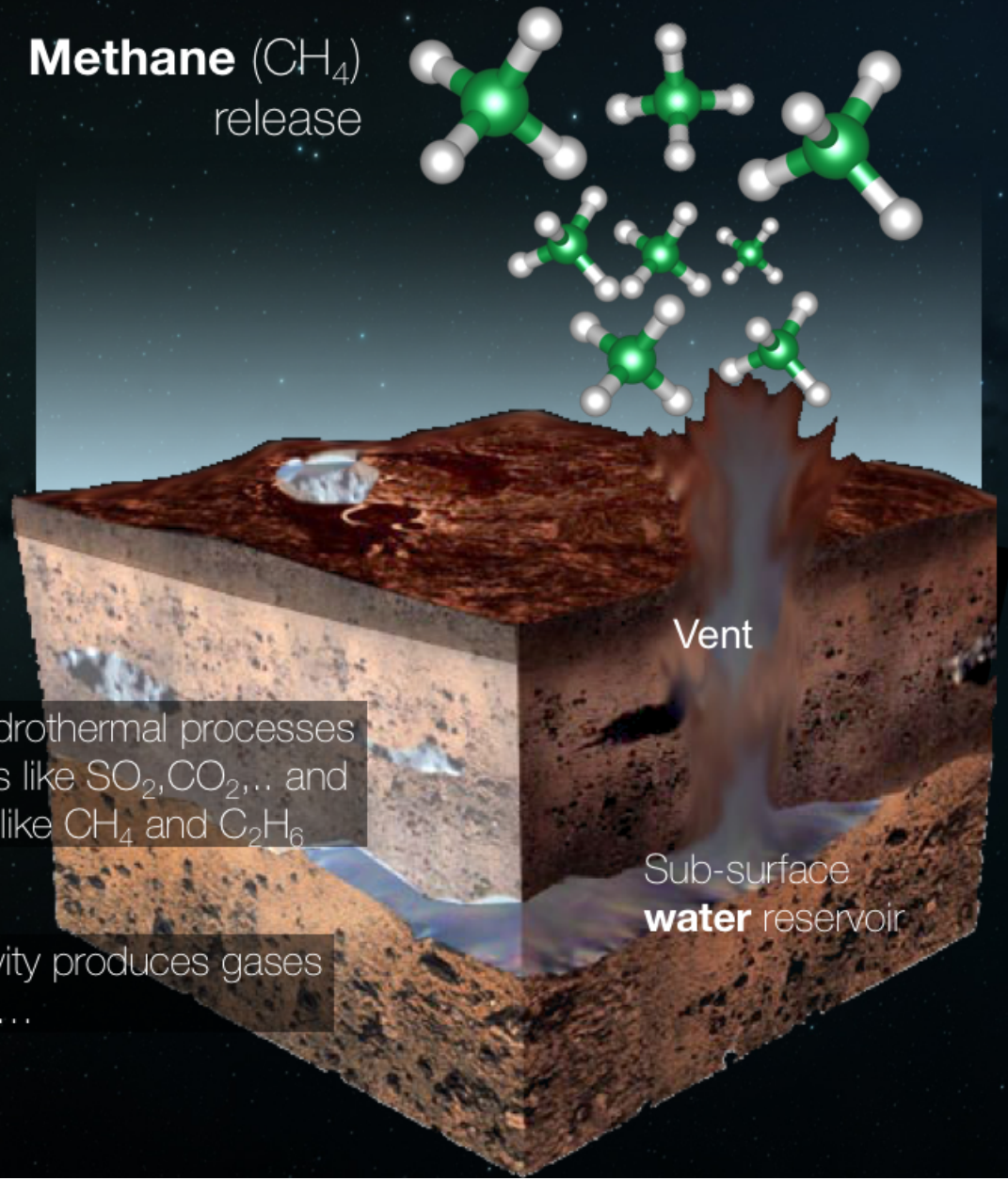
Any recent activity produces **chemical imbalances**
On Earth, methane is a powerful biomarker and sulfur dioxide is a strong geological indicator.

Volcanic or hydrothermal processes produce gases like SO_2,CO_2,.. and hydrocarbons like CH_4 and C_2H_6

Biological activity produces gases like CH_4, H_2S …



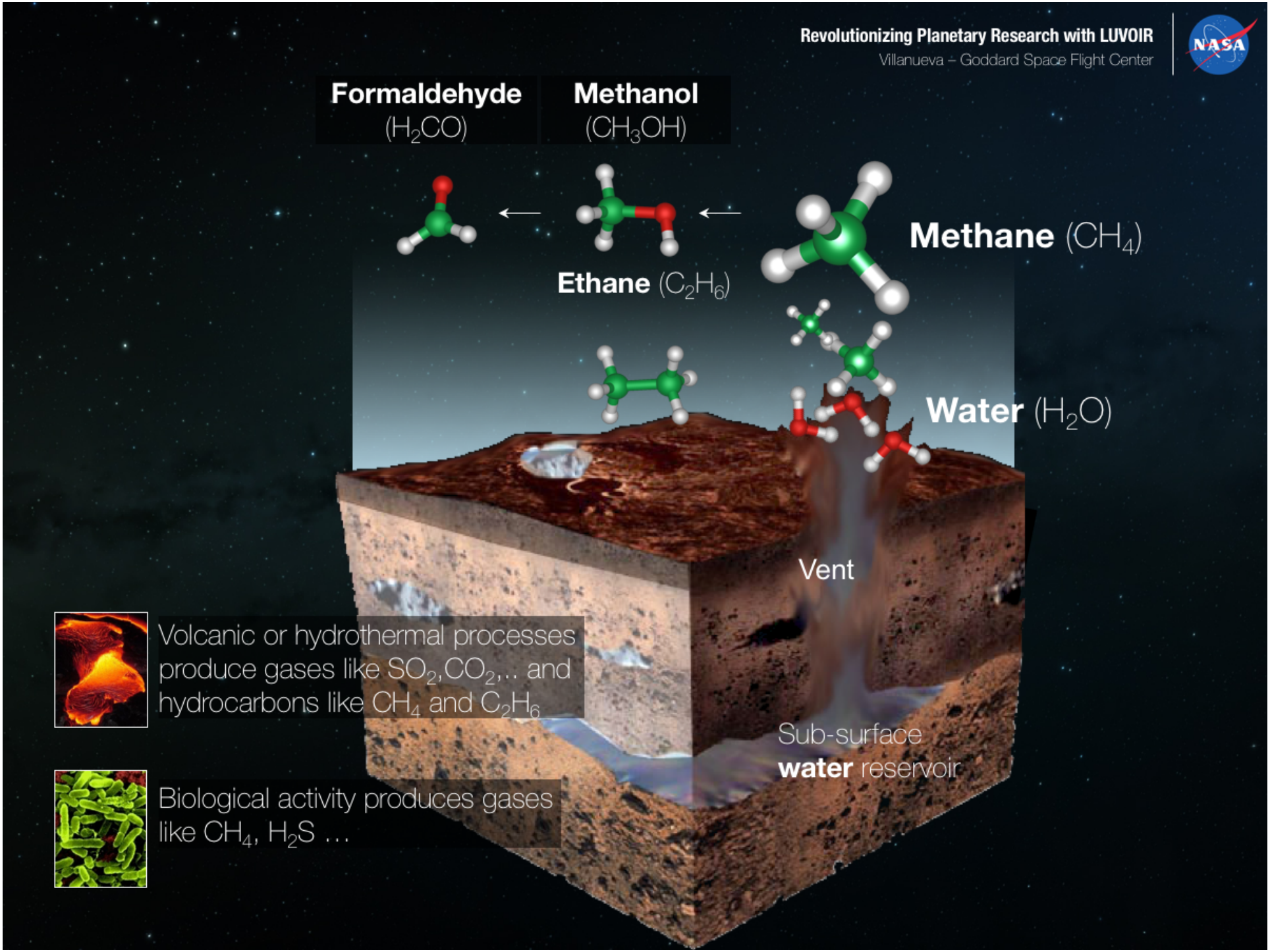
Methane (CH_4) release



Volcanic or hydrothermal processes produce gases like SO_2,CO_2,.. and hydrocarbons like CH_4 and C_2H_6

Biological activity produces gases like CH_4, H_2S …

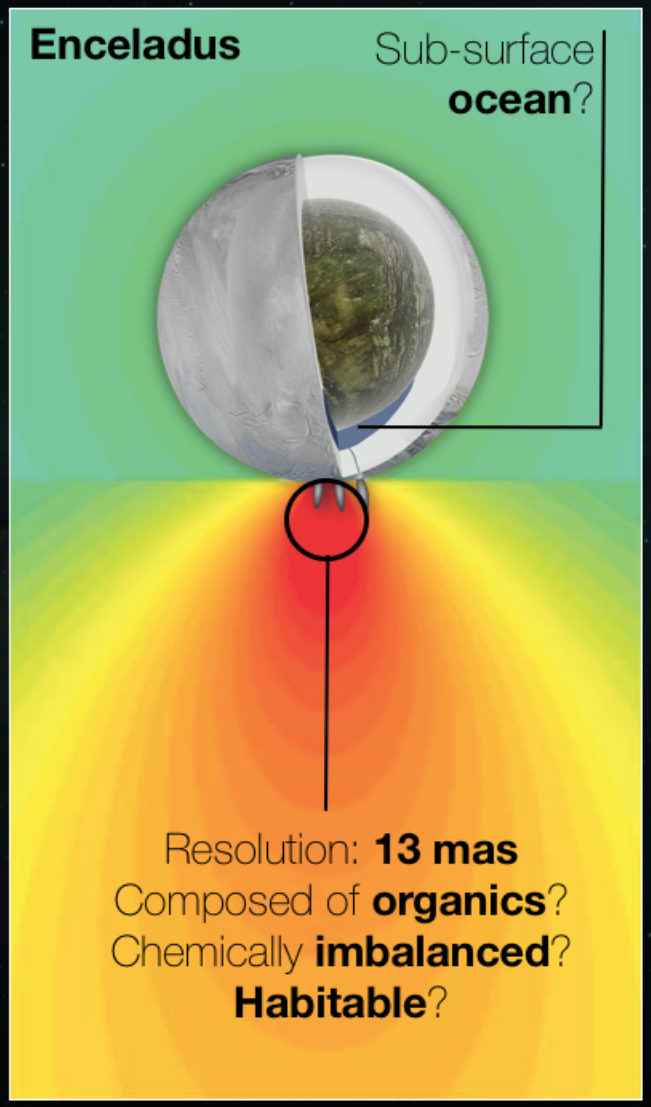
Chemistry in planetary atmospheres, then leads to a plethora of traceable **organic volatiles**

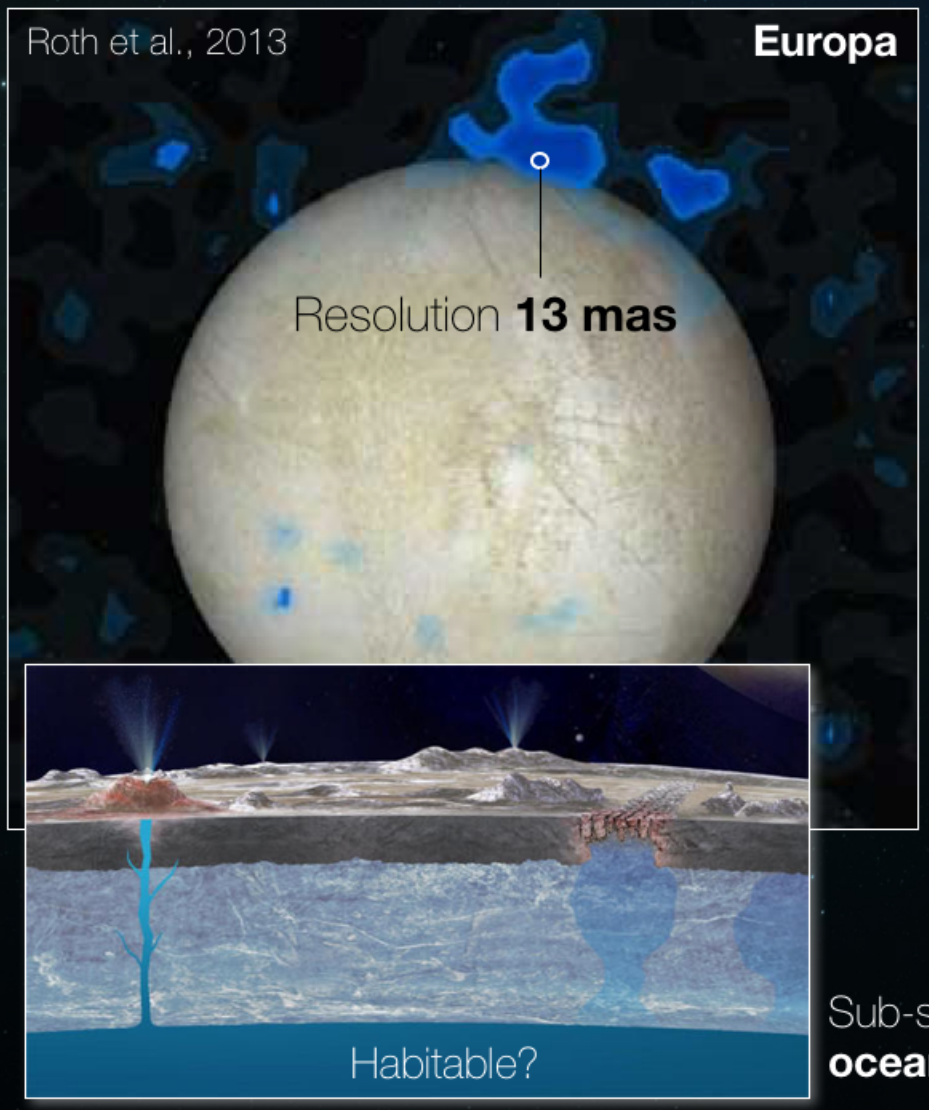

Formaldehyde
(H_2CO)
Methanol
(CH_3OH)
Ethane (C_2H_6)
Methane (CH_4)
Water (H_2O)
Vent
Sub-surface
water reservoir
Volcanic or hydrothermal processes produce gases like SO_2,CO_2,.. and hydrocarbons like CH_4 and C_2H_6
Biological activity produces gases like CH_4, H_2S …

Methane has been recently detected on Mars, yet organic species are marginally observable from ground – **Need for space observatory**

Mumma, Villanueva et al. 2009; Villanueva et al. 2009

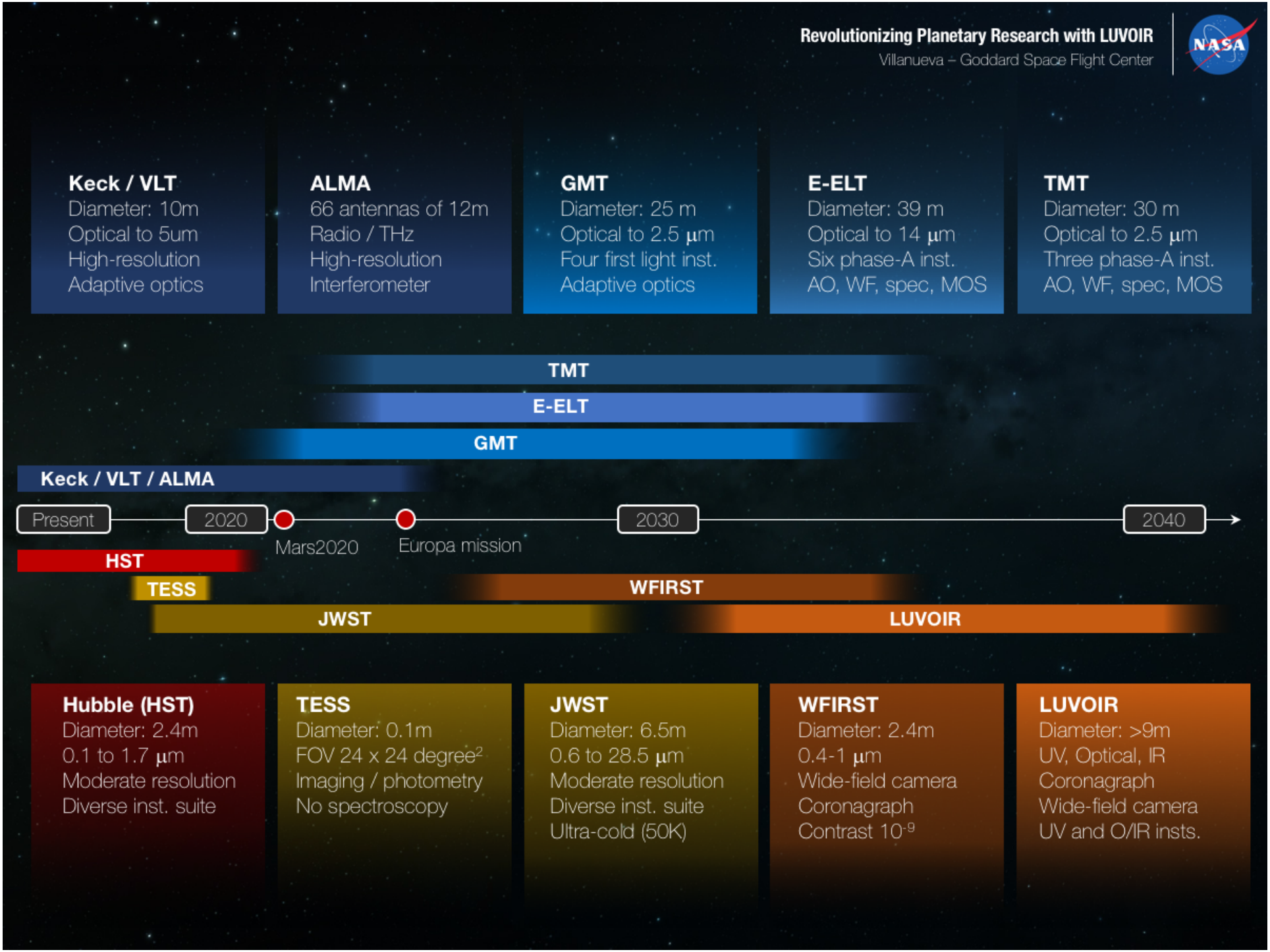
Plumes in Enceladus and Europa? Oceans?





What type of biology?

- Probing the **origin** of our Solar System
  - **Comets** / **asteroids** / **KBO**s (non-sidereal 60 mas/s)
  - **Organic** inventory and **isotopic** ratios
  - Access to **3.5 microns** (CH-stretch) and **EUV**
  - **Wide field of view** (>8 arcmin) and **IFU** spectroscopy
- Testing for ancient **habitability**
  - Access to **3.7 microns** (HDO fundamental) and **UV**
  - High flux **dynamic range** (weak and bright sources)
  - **High resolving power** (>50,000)
- Searching for **biology** / **geology**
  - Search for **imbalances** → broad spectral coverage
  - High **spatial** (D>10m) and **spectral** resolution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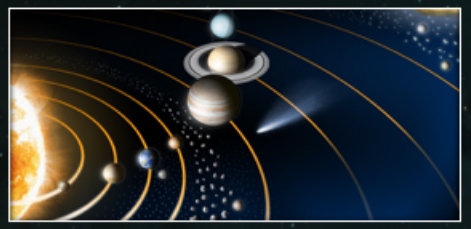
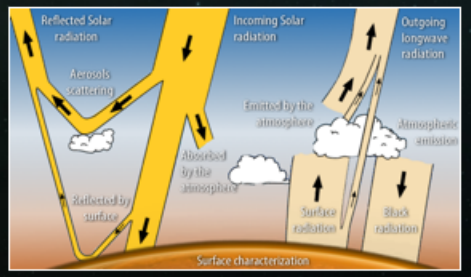
NASA
Keck / VLT
Diameter: 10m
Optical to 5um
High-resolution
Adaptive optics
ALMA
66 antennas of 12m
Radio / THz
High-resolution
Interferometer
GMT
Diameter: 25 m
Optical to 2.5 μm
Four first light inst.
Adaptive optics
E-ELT
Diameter: 39 m
Optical to 14 μm
Six phase-A inst.
AO, WF, spec, MOS
TMT
Diameter: 30 m
Optical to 2.5 μm
Three phase-A inst.
AO, WF, spec, MOS
TMT
E-ELT
GMT
Keck / VLT / ALMA
Present
2020
Mars2020
Europa mission
2030
2040
HST
TESS
WFIRST
JWST
LUVOIR
Hubble (HST)
Diameter: 2.4m
0.1 to 1.7 μm
Moderate resolution
Diverse inst. suite
TESS
Diameter: 0.1m
FOV 24 x 24 degree2
Imaging / photometry
No spectroscopy
JWST
Diameter: 6.5m
0.6 to 28.5 μm
Moderate resolution
Diverse inst. suite
Ultra-cold (50K)
WFIRST
Diameter: 2.4m
0.4-1 μm
Wide-field camera
Coronagraph
Contrast 10-9
LUVOIR
Diameter: >9m
UV, Optical, IR
Coronagraph
Wide-field camera
UV and O/IR insts.

To **synthesize** planetary spectra with **any** of these facilities, a new tool is now **online** (Planetary Spectrum Generator, **PSG**):

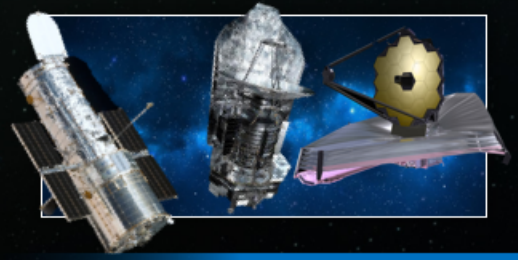
Spectra of **planets**, **exoplanets** and **small-bodies** from 0.1 μm to 100 mm (UV/Vis/near-IR/IR/far-IR/THz/sub-mm/Radio) from any observatory (e.g., JWST, ALMA, Keck, SOFIA), any orbiter (e.g., MRO, ExoMars, Cassini, New Horizons).



The tool has a **3D orbital calculator** for **most bodies** in the Solar system, and **all confirmed exoplanets**. Observing geometries are: observatory, from surface, nadir, limb, occultation.



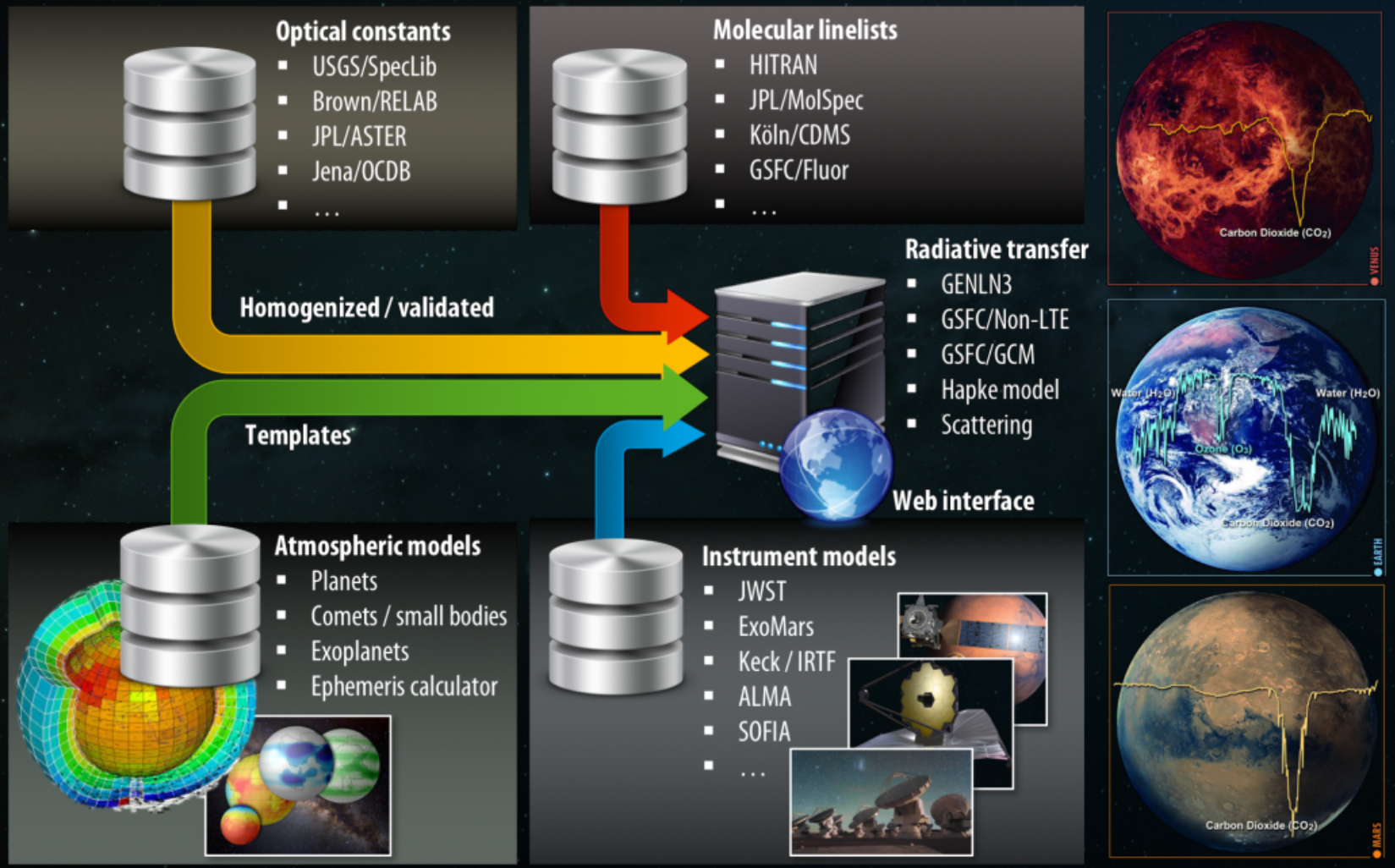
Radiative transfer performed with several models: GENLN3, correlated-K, non-LTE fluorescence, and surface models



It includes a noise and signal-to-noise calculator for quantum and thermal detectors, at any observatory.

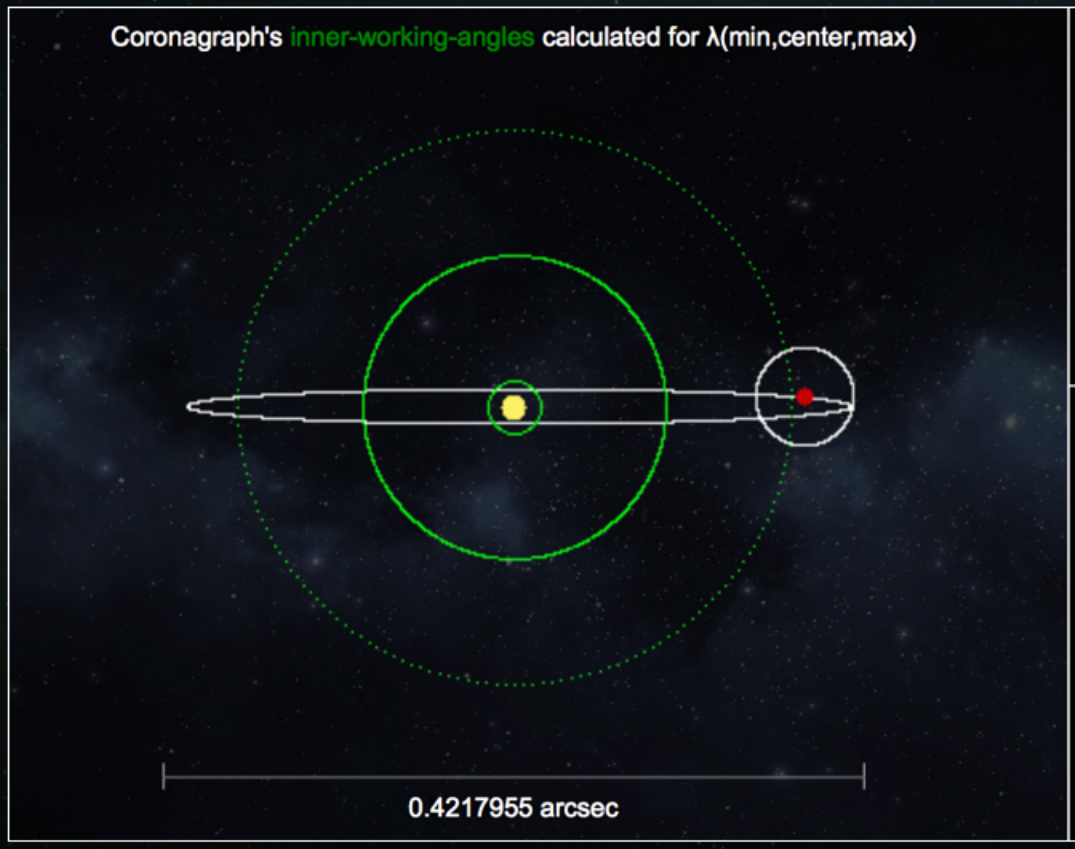
Revolutionizing Planetary Research with LUVOIR

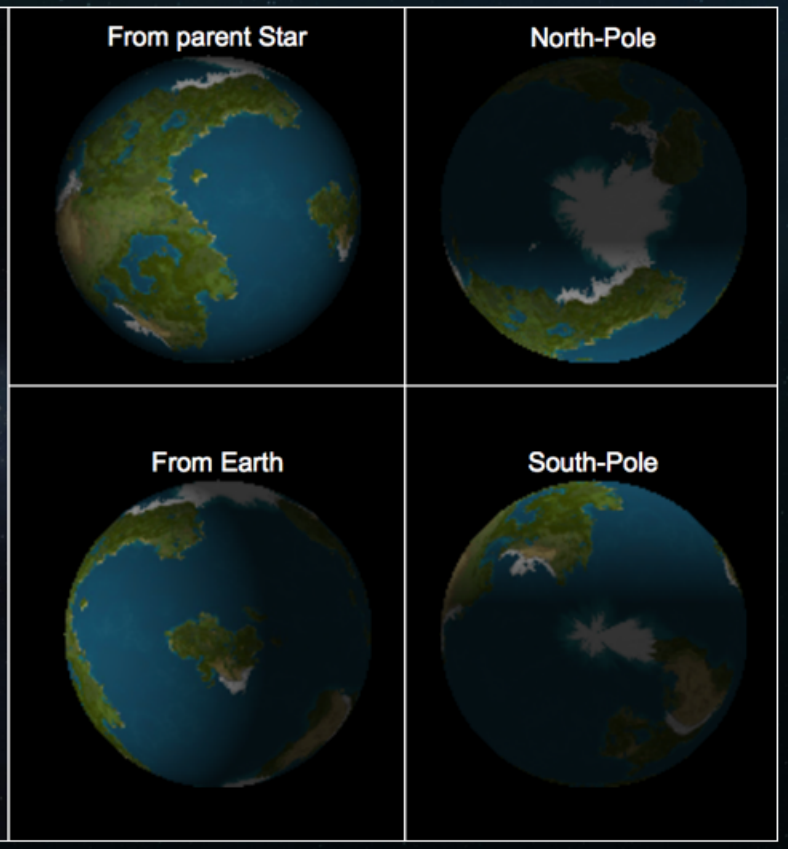
Villanueva – Goddard Space Flight Center



http://ssed.gsfc.nasa.gov/psg

Example of a **simulation** of an Earth-like **exoplanet** at 5pc with a **coronagraph** on LUVOIR





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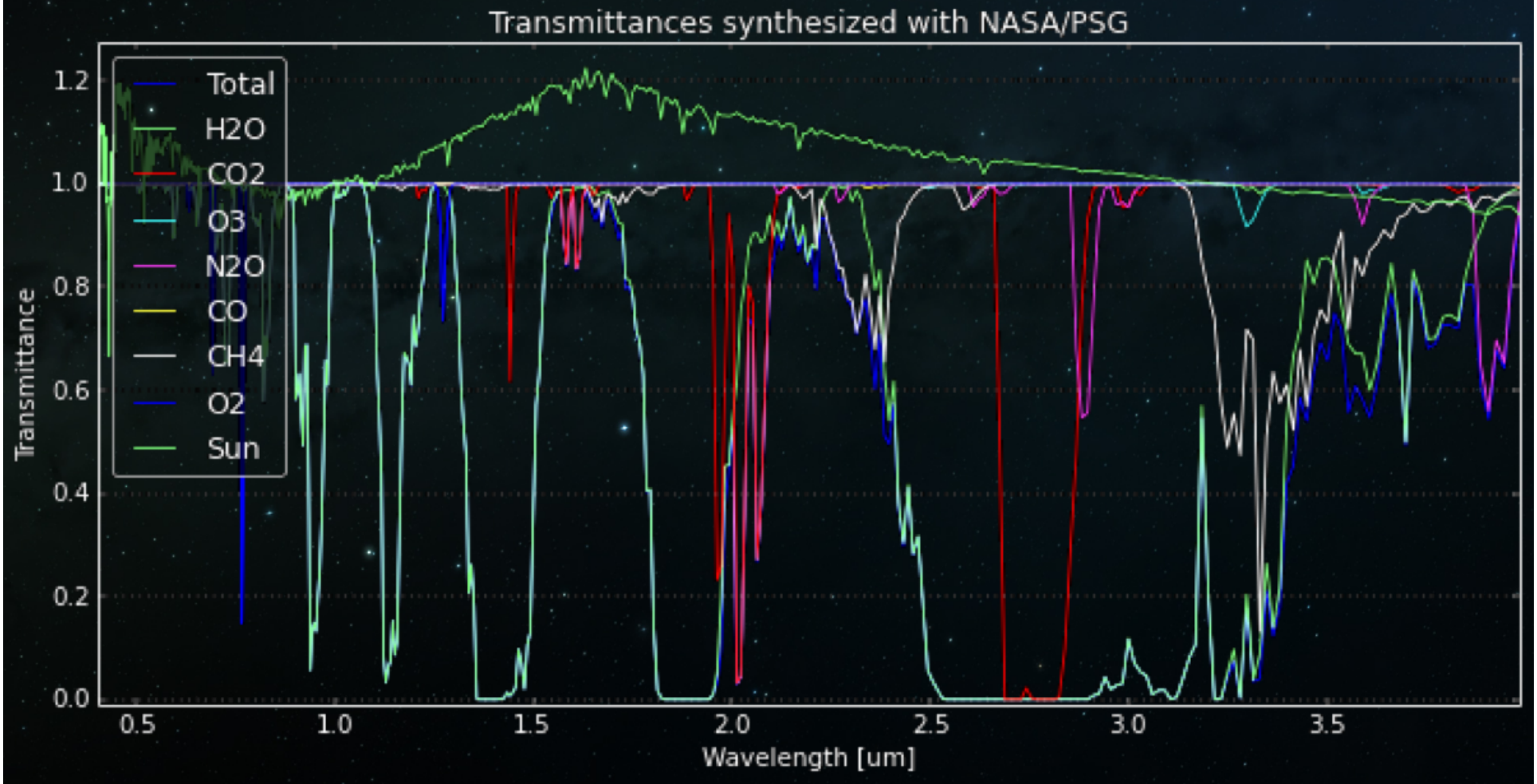

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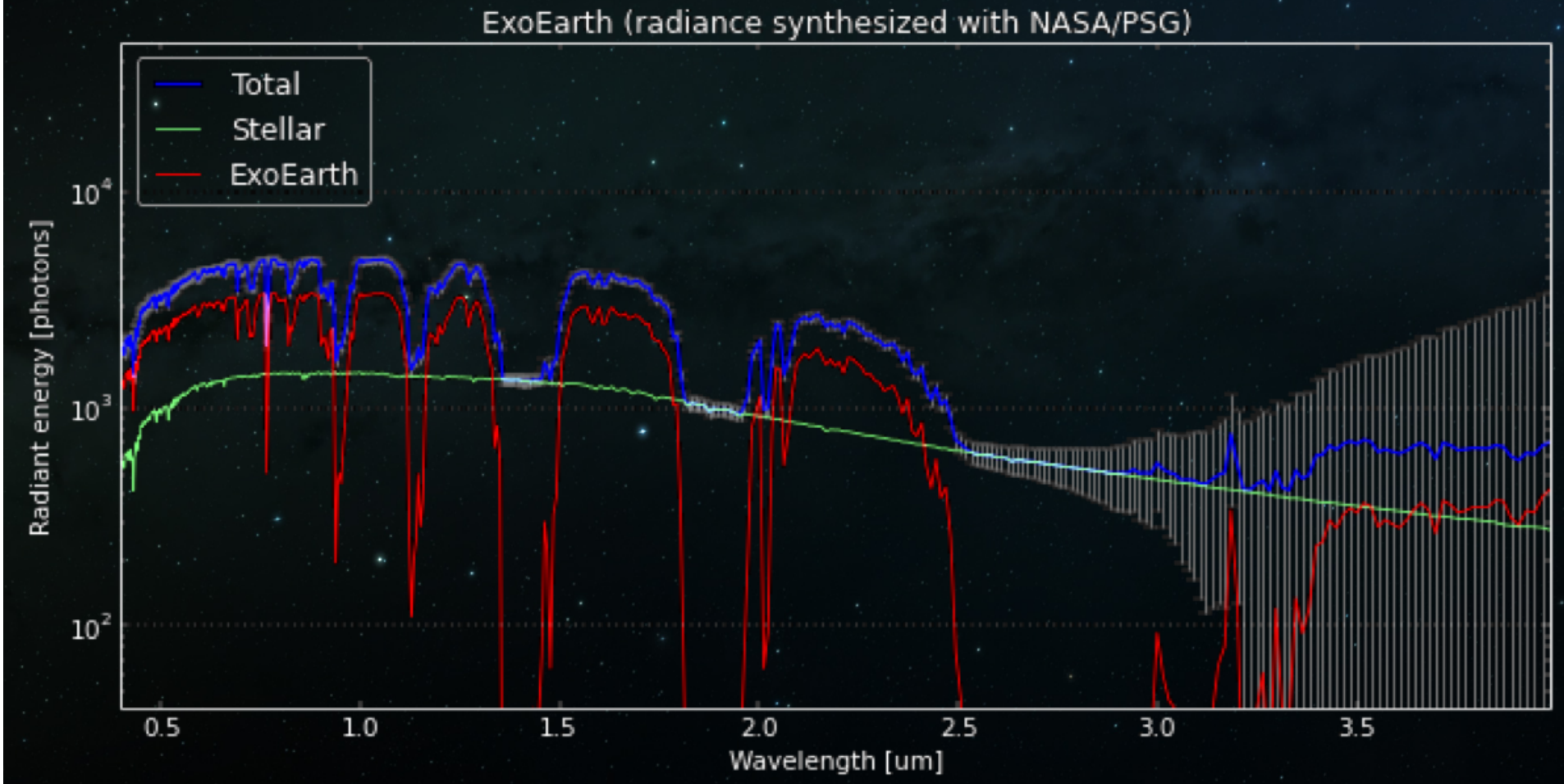
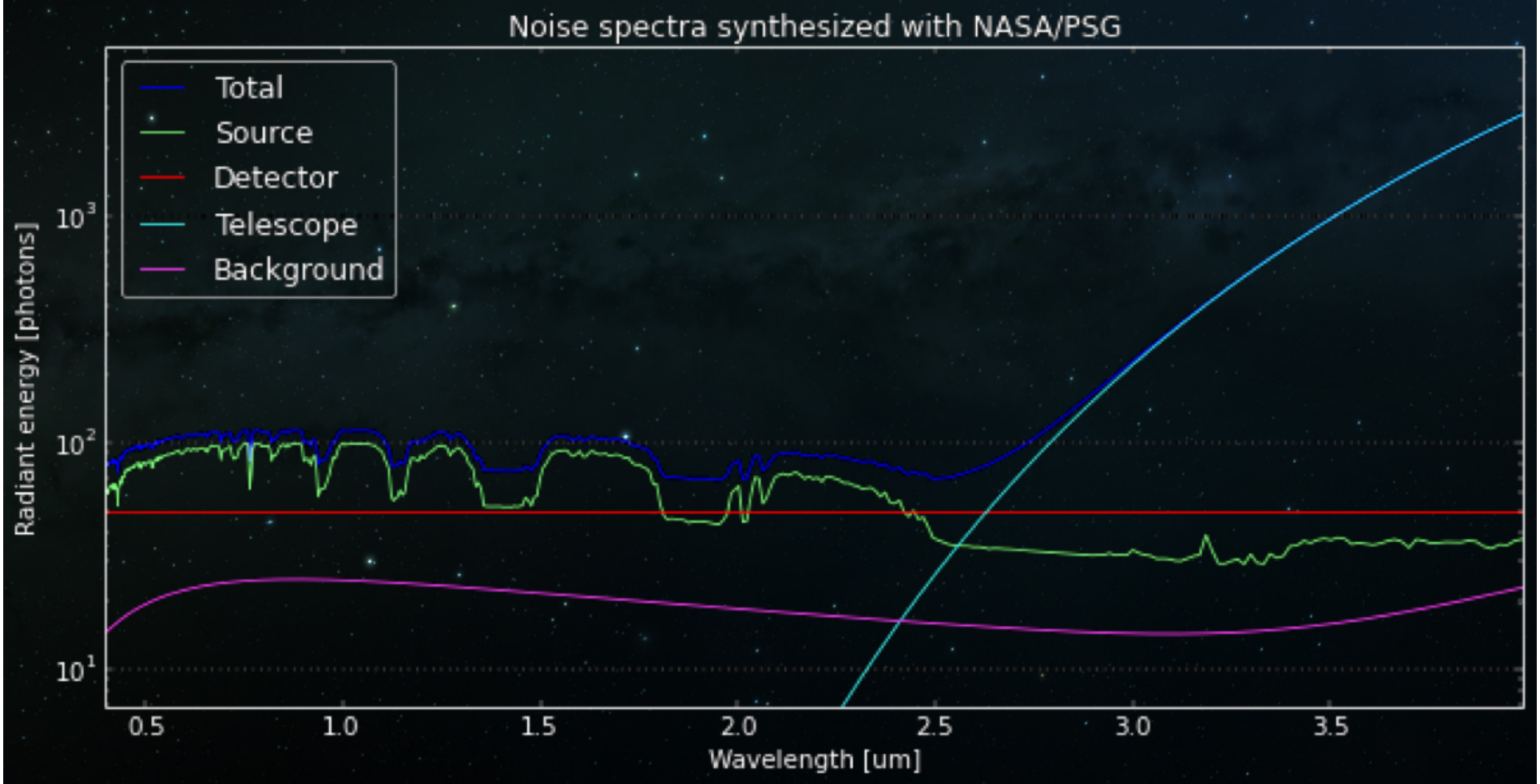


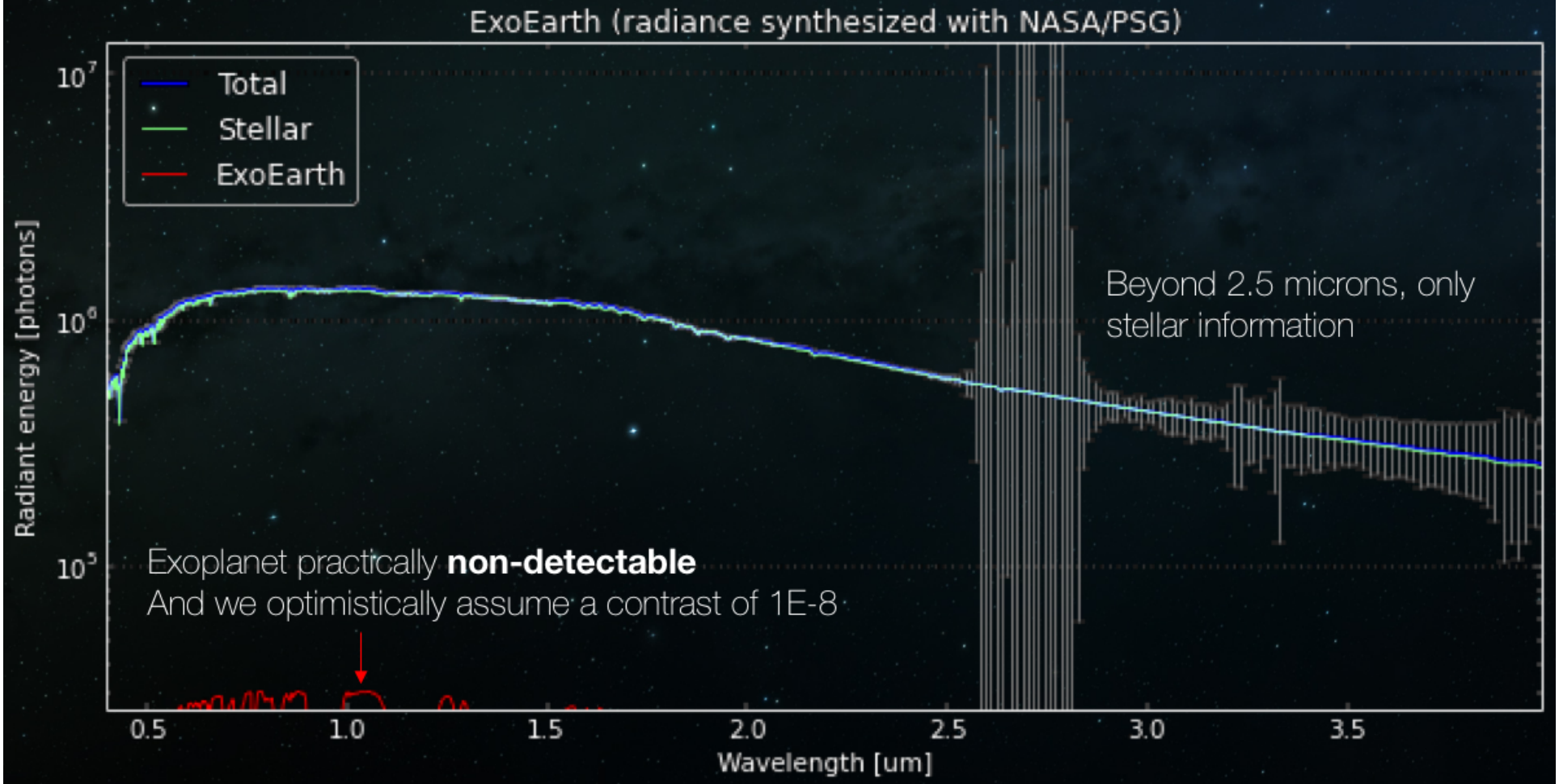
http://ssed.gsfc.nasa.gov/psg

Example of a **simulation** of an Earth-like **exoplanet** at 5pc with a **coronagraph** on LUVOIR

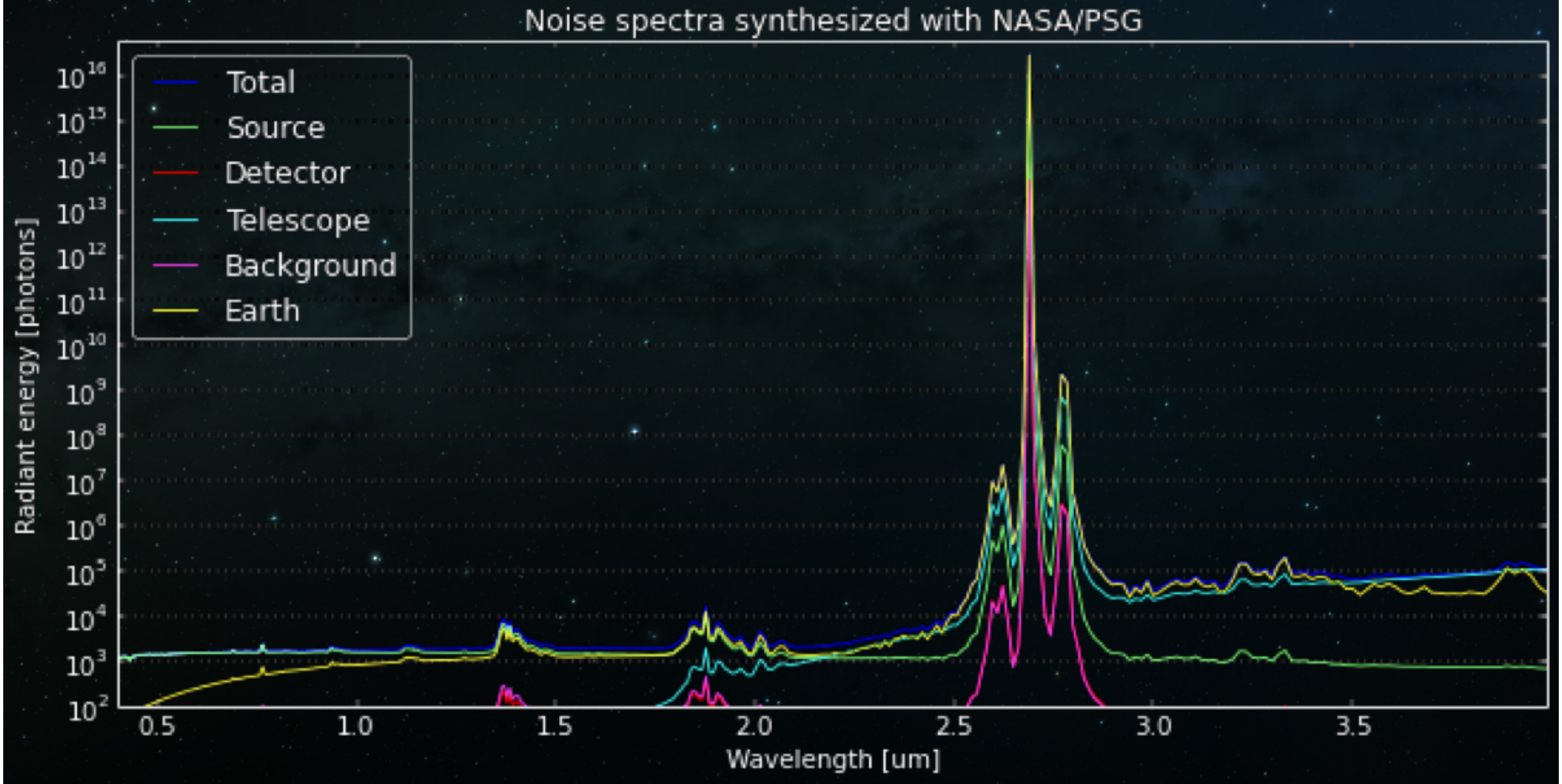


http://ssed.gsfc.nasa.gov/psg

Example of a **simulation** of an Earth-like **exoplanet** at 5pc with a **coronagraph** on a 30m ground-based telescope



Example of a **simulation** of an Earth-like **exoplanet** at 5pc with a **coronagraph** on a 30m ground-based telescope



http://ssed.gsfc.nasa.gov/psg

- Probing the **origin** of our Solar System
  - **Comets** / **asteroids** / **KBO**s (non-sidereal 60 mas/s)
  - **Organic** inventory and **isotopic** ratios
  - Access to **3.5 microns** (CH-stretch) and **EUV**
  - **Wide field of view** (>8 arcmin) and **IFU** spectroscopy
- Testing for ancient **habitability**
  - Access to **3.7 microns** (HDO fundamental) and **UV**
  - High flux **dynamic range** (weak and bright sources)
  - **High resolving power** (>50,000)
- Searching for **biology** / **geology**
  - Search for **imbalances** → broad spectral coverage
  - High **spatial** (D>10m) and **spectral** resolution